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APRIL 26 TO 29, 1939
WASHINGTON, D. C.

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## SECTION OF HYDROLOGY

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# AMERICAN GEOPHYSICAL UNION

## Twentieth Annual Meeting

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Washington, D. C.
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# ANNUAL REPORTS OF PERMANENT RESEARCH COMMITTEES FOR 1938-39

## REPORT OF COMMITTEE ON SNOW, 1938-1939

J. E. Church, Chairman

### Growth

It is now 30 years since forecasts of stream-flow were first attempted. Their value and relative magnitude are shown by the following warning sent out by the California Director of Public Works:

"A warning to agriculturists, irrigation- and water-districts, the mining industry and power-companies to conserve to the utmost their impounded water-supplies was sounded by Director of Public Works Frank W. Clark today in submitting to Governor Culbert L. Olson the annual forecasts of runoff from California watersheds.

"These forecasts are based on snow-surveys interpreted by the State Division of Water Resources which show that this year's snow-pack is only 50 per cent of normal as contrasted with a pack which was 50 per cent above normal last year at this time.

"'While there is no need for alarm,' Director Clark said, 'it is advisable that every gallon of impounded water be carefully conserved during this summer.'

"This year, on account of the extreme deficiency in rainfall in the central valleys of California, the Division of Water Resources has been besieged with requests for data on what to expect from the mountain snow-pack. Engineers of the City of San Francisco, the East Bay Municipal Utility District, the Pacific Gas and Electric Company, and irrigation-districts of the Sacramento and San Joaquin valleys have kept in close touch with the Division in order to avail themselves of the information gathered during the snow-surveys.

"The Tulare Lake farmers who were flooded out last year have been awaiting release of the Snow-Survey Bulletin issued today in order to determine whether they should pump out their flooded reclamation-districts and plant again this year. With assurances contained in the bulletin that no runoff from the Kings, Kaweah, and Kern rivers will this year spill over into Tulare Lake to overtop their levees and drown out their wheat, cotton, and sugar-beet crops, they are already pumping out the flooded areas of Tulare Lake.

"Advance knowledge of the runoff is necessary to determine crop-planting schedules, power-generation, and reservoir-operations so that no water shall be wasted early in the year that may be urgently needed later on.

"The combined low-water flow from the Sacramento and San Joaquin rivers determines the extent to which salinity from the ocean will creep up through San Francisco, San Pablo, and Suisun bays into the sloughs over the levees. Salt water ruins the crops. The snow-surveys enable the Division of Water Resources to estimate next summer's low-water flows and forecast the extent of the salinity-penetration, determining where and to what extent pumping can be done before the water gets salt enough to damage the crops.

"Because of public demand the mountain network of snow-measuring stations has steadily spread until today it covers the entire Sierra from the Klamath to the Kern. It embraces the Owens Valley where the water from the snow-pack supplies water to the City of Los Angeles through the Los Angeles Aqueduct. Snow-measurements are also made in Southern California on the headwaters of San Antonio Creek on which a disastrous flood occurred last year.

"This year during the two weeks required to make snow-pack measurements above 150 men under the general supervision of Fred Paget of the Division of Water Resources participated in the snow-patrol, traveling an aggregate total of about 45,000 miles to measure a snow-pack covering an area of approximately 17,000 square miles. Some of the patrols were long, some were short, most of them were arduous, and many of them were hazardous. Shelter-cabins along the route were stocked with food and bedding but personal effects and the instruments for measuring the water-content of the snow-pack had to be carried by the surveyors.

"Most of the 150 men needed to make the snow-surveys are employees of cooperating agencies. Standard equipment for making the measurements is supplied by the State and uniform methods are taught the snow-surveyors. Important as the forecasts of runoff, stream-flow, and salinity are to the entire State of California, the snow-surveys up to date have been carried on with very little public expense. Because of lack of funds the Division of Water Resources can delegate only one engineer full time to this work."

This is a tribute to the far-sightedness of Major Paul M. Norboe, then Chief Assistant State Engineer of California, who sought some means of estimating the seasonal water-resources of his

State and welcomed the Nevada Forecast System at the time of its greatest crisis.

Snow-survey forecasts are now being made by the Bureau of Agricultural Engineering throughout the mountain areas of the West in cooperation with States, other Federal departments, municipalities, irrigation-districts, and power-companies, while similar surveys and forecasts are being made in the Northeastern States, Newfoundland, and Canada. The Merrimack Basin in New Hampshire has now been added to the list. The 250 snow-survey courses in the Sierra Nevada are therefore only a fraction of the whole.

Added to this are the suggestions of Jesse C. Wanslee that snow-surveys in Arizona would greatly aid the cattle-men there in determining probable summer pasturage, and requests from the Great Plains region for forecasts of stream-flow from the Continental Divide as an indication of the wisdom of planting crops. Miners also are seeking advice regarding the possibility of developing water for their claims or estimating the probable seepage of water into their mines.

Safety in skiing and transport has brought an increasing need for knowledge of the physics of snow and a uniform nomenclature of snow.

Of greater import still is the international expansion of interest in snow and ice under the direction of an International Commission of Snow with a membership of 28 countries and personnel of 172. This Commission has the functions of the Research Committee on Snow but with international interests. It is specially fitting that at this time the latter should be the guest of America at the coming September meeting at Washington, D. C.

## Personnel of Committee

To the Committee, which has been steadily expanding since its organization in 1931, has been added Phil E. Church, Professor of Geography and Meteorology at the University of Washington, as representative for the Northwest in snow-physics and snow-nomenclature. He has long been a leader in the Section of Meteorology of the Union.

The entire membership of the Committee is commended to the new Executive Committee which will take over the administration of the Section of Hydrology for the coming period of 1939-1942. Since research is of slower growth than its applications, frequent change is undesirable and disconcerting.

## The snow-cover

Experience in temperature oscillation during past years seems to indicate that a cold winter on the Atlantic Seaboard is accompanied by a warm winter on the Pacific and vice versa.

Precipitation also might seem to have a similar balance. The United Press in an interview with the Chairman in early March assumed this but applied it to the two sides of the Continental Divide with resulting consternation to the public, who were informed of threatened drought in the Pacific West and floods in the Mississippi Basin.

This pattern of scarcity and abundance covered rather the entire width of the United States but without the extremes forecasted by the press. In general, the snow-cover was heaviest on the Atlantic Seaboard of the United States and Canada and diminished from the Great Plains to the Pacific with local spottedness in uniformity.

In Newfoundland the snow-cover was above the average for nine years, in New England above general average, and in New York unusually heavy. On the Continental Divide both in the United States and in Canada the cover oscillated slightly above or below normal, while in the Sierra Nevada the snow-pack fell to slightly less than one-half of normal.

Intensifying the snow-cover deficiency in the West is the high winter and spring temperature that has advanced the season fully a month and greatly melted the already thin snow-cover, with probability of lack of natural flow in late autumn. However, held-over storage in reservoirs from last season, which was unusually heavy, and unusually abundant soil-moisture will safeguard most areas from destructive drought.

Details are given here and there in the regional reports. Much of the information has been gathered cooperatively by the Bureau of Agricultural Engineering.

## Regional and project reports

Following last year's plan, only the reports of activity will be given here, while the suggestions for research problems will be presented under the heading of Research.

Newfoundland (ERIC HINTON)

Although Grand Lake was entirely frozen over at the time of the snow-survey, the ice in the neighborhood of Glover Island was unsafe for travelling over. Consequently two subareas were inaccessible for the purpose of survey. It has therefore been necessary to deduce the probable water-content of the snow in these areas.

Owing to the fact that logging operations have denuded the timber in two other areas, there will be no satisfactory sampling sites thereabouts until the young trees have grown sufficiently to prevent ground-drift.

The forecasted runoff from March 27 to June 15 is approximately 12 per cent greater than the average of the past 13 spring floods.

Lower Canada (M. BALLS)

I am very sorry that I am not yet in a position to submit any material regarding the forecasting of runoff in this area. This is due to the fact that our difficulties in making forecasts have not yet been solved. We are still very much interested, however, and are continuing our snow-surveys as usual in the Saint Maurice River Watershed. Snow-surveys are also being continued by the Gatineau Power Company in the Gatineau River Drainage Basin, and it is probable that annual surveys will be undertaken in the Saguenay River Watershed above Lake St. John by next year.

New England--particularly Maine (PAUL L. BEAN)

The water year from October 1, 1938, to April 4, 1939, in northeastern New England rates about average in the amount of precipitation, with a very heavy snow-cover and a heavy water-content.

At elevations of 4000 feet above sea-level in the White Mountain area, the depth of snow is about 122 inches and of high density. At elevations from 2000 to 4000 feet, about 50 inches of snow, with a water-content varying from ten to thirteen inches. Below elevation 2000 feet to sea-level, the snow-cover is from 18 inches to 36 inches in depth, with a water-content from six inches to ten inches.

Precipitation in the form of snow is generally the second heaviest within the period of record, totaling as of even date 126.6 inches and every prospect of being further increased. In 1897-98 precipitation in the form of snow totaled 134.5 inches. Records are taken at Rumford, Maine.

Aside from the magnitude of the snow-cover, the outstanding characteristic of the season is the very late spring break-up. The close of the winter season has presented very low temperatures and a high barometer caused by cold air-masses of Canadian origin flowing into this area. Ice-cover on the lakes is unusually heavy, showing 36 inches to 48 inches of clear ice, with a heavy snow-cover. The rivers show from 24 inches to 36 inches of ice.

Our problems to be investigated are the same as last year, namely, snow-evaporation, ground-water and capacity of ground to absorb water, and maximum rates of runoff due to melting snow. They will be with us for many years.

In our snow-survey work our efforts have been confined chiefly to improving existing stations and changing locations to different altitudes. The number of stations remains about the same.

Extension of snow-surveying is being carried out by one of the water-power companies in this area, the work being done to fit in with existing snow-traverses and will result in more actual stations and in more detail. We shall also obtain the results of snow-surveys now being made in the White Mountain area, the maximum flood producing area in this region.

I would reiterate the value of snow-surveying in our work. It is the difference between guessing and closely accurate knowledge. Its value is worth real money.

Southern New England (H. I. BALDWIN)

Interest in snow-surveying in New Hampshire continues to grow. Snow-sampling has been carried out during the winter of 1938-39 by the New Hampshire Public Service Commission and by the Flood Control Office of the Northeastern Forest Experiment Station, located at 28 North Main Street, Concord, New Hampshire. Snow-depths have also been recorded at about 100 stations by persons interested in winter sports. The Flood Control Office has several men in the field continuously, using samplers patterned after the Mount Rose model, but with certain original modifications. They propose following the changes in snow-density daily in the forest and in the open until the last trace of snow disappears. At the end of March there was still a complete snow-cover over the state with depths ranging from six inches in the southeastern lowlands to ten feet and over in White Mountains.

(a) The Merrimack Basin (JOHN V. SALO, Public Service Co. of New Hampshire)

We have been fortunate enough to be able to examine a copy of the Proceedings of the Western Interstate Snow-Survey Conference which was held at Davis, California, on January 8, 1938.

This literature is of particular interest to us for we are just completing our second year of snow-survey field-work in the Merrimack River Basin. The contributions and discussions which you and your associates have made in this field will prove invaluable to us for we are still in the preliminary stages of our work.

New York State (E. S. CULLINGS)

I am sending you the attached memorandum which briefly describes snow-conditions in the Adirondack Region during the past winter. Arthur W. Harrington, District Engineer, United States Geological Survey, is now acting as chairman of the New York Cooperative Snow-survey and, through cooperative arrangement, has extended it to cover the Mohawk Valley and the Catskill Region as well as the Adirondack Region.

In the Adirondack Region the snow during the winter of 1938-39 was rather light until mid-winter, after which the snowfall was heavier and the snow accumulated to somewhat greater depth than in the normal winter. At the end of January the water-content of the snow varied from three inches around the margins of the Adirondack Plateau to six inches in the interior. At the end of February the quantity of water stored on the ground in the form of snow had increased to six inches along the westerly slope and to ten inches on the headwaters of the Mohawk River, which drains the southerly slope. On March 20, the date of the last survey, water-content of the accumulated snow had increased quite uniformly to a depth of from six to seven inches over the whole interior region and to twelve inches on a small area at the head of West Canada Creek, a tributary of the Mohawk River.

The temperature was somewhat above normal in February, resulting in some melting of the snow and increased runoff, but during March the temperature was below normal, and but little of the snow had melted by the end of the month. At this date, April 4, the snow is beginning to melt and the streams are rising.

Mr. Harrington reports as follows: "The survey of March 27, the last scheduled survey of the current season, finds an unusually heavy accumulation of snow, the cover extending over practically the entire State."

## North Continental Divide

(a) Bow River Basin (O. H. HOOVER)

Various snow- and ice-fields are to be found on the upper reaches and tributaries of the Bow River and these to a large extent retard the stream-flow to a later period in the summer of each year. As well normal and flood-flow conditions are to a degree dependent upon this snow-deposit, and as the waters of the Bow River from a power- and irrigation-point of view, have now become one of the Alberta's primary resources, it has been decided, for forecasting purposes, to collect some data each spring on the snow-deposit of the Basin.

From a general observation in the Bow Valley on March 31, 1939, one could observe that the snow-cover was less than at the same date in 1938, and more than at the time of the survey in 1937. The meteorological observers' records at Lake Louise show a snowfall of only 112.5 inches from October, 1938, to March, 1939, which according to former meteorological records is the lowest snowfall in ten years.

By the snow-survey just completed however and from 110 samples obtained from four snow-courses a mean water-content of 6.2 inches was found for the area. This water-content might be expected to produce a flow of about 587,000 acre-feet in the Bow River at Banff, or approximately 88 per cent of average during April, May, June, and July.

In using the figures of this forecast it should be borne in mind that the runoff-percentage can be very materially disturbed by torrential rains that occur spasmodically during June and July in the Bow River Valley.

Table 1--Total annual snowfall as recorded at the Meteorological Station at Lake Louise, 1929-39

| Year | Snowfall | Year | Snowfall |
|---|---|---|---|
| | inches | | inches |
| 1929-30 | 163.7 | 1934-35 | 150.9 |
| 1930-31 | 130.6 | 1935-36 | 147.6 |
| 1931-32 | 161.1 | 1936-37 | 133.1 |
| 1932-33 | 175.2 | 1937-38 | 183.5 |
| 1933-34 | 225.9 | 1938-39 | 112.5 |

(b) Upper Missouri Basin (D. B. FREEMAN)

A. H. Tuttle is now the District Engineer for the United States Geological Survey at Helena, replacing Mr. Lamb. The field-work involved in the snow-surveys for the Missouri Headwaters Region is being done under the direction of A. H. Tuttle from funds provided by the War Department.

Snow-surveys were made this year on April 1 at all except one of the regularly established courses. These surveys show that the water-content on April 1, 1939, was about 20 per cent less than it was on April 1, 1938. However, the water-content on March 1, 1939, was 15 per cent greater than it was on March 1, 1938, and also the greatest since the establishment of the courses in 1934. The low-water content on April 1 may be attributed to the combined effects of a deficiency of snowfall during March and considerable melting which took place as a result of a period of unusually warm weather.

It is not believed that the reduction in snow-cover which occurred during March will have a very great effect on the total probable runoff above Fort Peck during the months April to July, for which period the forecast of this Office is made. Consideration of all the factors involved appears to justify the conclusion that a normal runoff this year may be expected. The normal runoff for the drainage-area above Fort Peck for the period April to July is considered to be 4,500,000 acre-feet.

(c) Columbia Basin (JAMES C. MARR)

Compared with previous years the present snow-cover varies in different sections of Columbia Basin. The low snow in all sections of Columbia Basin has disappeared. At the elevations along Continental, Bitterroot and Cascade divides, where the snow-cover usually remains intact until April 1 or after, the amount of snow-water at present approaches that of 1938.

The amount of water impounded in most of the reservoirs of Columbia Basin is much greater than is usually the case at this time of the year and in most cases would be still greater were it not for the fact that water has been allowed to pass as a flood-control measure. With a few exceptions the storage will equal or exceed that of last year and in most cases reservoirs will fill to capacity.

## South Continental Divide

(a) South Platte and Arkansas basins (R. L. PARSHALL)

The water-content of the snow in the mountains in Colorado is slightly less than it was a year ago. On the Arkansas River drainage, the water-content is ten per cent less than last year, as shown by nine courses, and on the South Platte drainage it is five per cent less, as shown by 13 courses. Although there is a deficiency in the water-content of the snow in the mountain areas, there is much more water in storage in reservoirs and soil than there was last year, and consequently no shortage of water for irrigation is expected at this time even though the runoff will be less this year. If, however, snowfall in the mountains during April is below normal, the prospects for the irrigation-water supply for the late season will not be so favorable, particularly for canals without storage rights.

(b) Rio Grande (R. L. PARSHALL)

In the Middle Rio Grande Conservancy District in New Mexico there is more than normal moisture in the ground. In the lower valley of the Rio Grande, soil-moisture conditions are normal.

Early melting of snow-cover on the Watershed of the Rio Grande in Colorado and New Mexico has reduced materially the amount available for late runoff. Fifteen snow-courses on the Rio Grande and tributaries show an average water-content of 5.4 inches, whereas last year at this time it was 9.7 inches. Unless considerable snow accumulates in the high mountain areas during April, the runoff of the Rio Grande will be considerably less than last year.

(c) Colorado Basin (R. L. PARSHALL)

Runoff from the Colorado above Grand Junction will probably be slightly less than last year. There has been some loss of snow-cover caused by early melting, but normal snowfall during April will improve conditions materially. On April 1, 1939, the average water-content of the snow on the 20 courses on the watershed of the upper Colorado was 14.0 inches. Last year at this time it was 15.5 inches. However, snow-depths on the White and Yampa river watersheds are also less than last year. On the watersheds of the Gunnison, Dolores, and San Juan the snow-cover is definitely less than last year, and the runoff from these watersheds will be below normal unless conditions are improved substantially during April. Conditions on the Gila in Arizona and New Mexico are causing apprehension. Soil-moisture is deficient, and the water in storage is less than one-half of that last year. Executive measures have been taken with consequent court action. There is very little snow left in the mountains and the snow accumulated earlier in the winter melted during the warm weather in March without appreciably increasing the runoff from the streams.

Utah (GEORGE D. CLYDE)

The Utah cooperative network is continuing to function very satisfactorily in the making of snow-surveys. No new courses have been established during the year. An analysis of our records indicates that several of our courses are superfluous, and that our forecasts will be just as accurate if we drop them out. It is proposed, therefore, that we begin weeding out the unnecessary courses from the Utah network.

Regarding water-supply conditions in Utah for 1939, in general the prospects are fair, the storage-reservoirs being pretty well filled throughout the State, but the snow-cover is such that the users of water from those streams having no storage will probably suffer a shortage of 25 to 50 per cent of that in 1938. The runoff in 1938, however, was exceptionally good and no serious water-shortage is anticipated.

British Columbia R. C. FARROW)

In the southern parts of the Province covered by our snow-survey systems the winter precipitation regarded as a whole was about normal; in distribution, however, it tended to diminish eastwards, being well above normal in the Coastal Belt, west of the Coast Range Divide; above normal in the Okanagan, and varying considerably in the Kootenay-Columbia Basin, where the northern part received normal or better snowfall, the Central part less than normal, and the southern portion varying both sides of normal.

In some parts of the interior rapid thawing due to excessively high temperatures commenced some two weeks earlier than usual. This early thawing probably affected several snow-courses, to the extent that actual runoff may exceed expectations as indicated by these courses.

In all areas where summer runoff is of prime importance the potential supply as stored in the form of snow is very close to normal or above it, and there should be no serious shortage during the period April to August, particularly where there is any considerable storage. On streams where there is neither natural nor artificial storage, the sufficiency will of course depend on climatic conditions during the ensuing months.

There is no potential flood-hazard from abnormal snow-cover at this time; future conditions in this regard will therefore depend entirely on the rate of melting as governed by temperature and rainfall.

On the majority of snow-courses there is little frost in the ground beneath the snow-mantle.

Adjacent to Vancouver the snow water-content is slightly above normal. Further inland along the Fraser River, it is well above the short term normal in the Stave Lake Area, courses showing up to 150 per cent of normal. Early summer rains in this region, however, have a marked effect in reducing or increasing snow-runoff.

Upper Columbia River

The snowfall in general appears to have been fairly uniform and slightly above normal. It is estimated that the runoff at Golden and at Revelstoke will be about 105 per cent of normal or about 2,200,000 acre-feet at the former place and about 19,000,000 acre-feet at the latter, from April 1 to August 31, while at Trail it is estimated at 98 per cent of normal or a runoff of about 37,000,000 acre-feet.

With only two to five years snow-course records to work from, these estimates must of course only be regarded as general indications. They are supported in general though by precipitation-data, and by established Kootenay-Columbia runoff-ratios.

News notes--Last February the writer visited and sampled all the Columbia-Kootenay snow-courses, instructing the different cooperators and snow-surveyors who have agreed to look after the various courses. Their initial efforts in making the end-of-March samplings appear to have been satisfactory, and no difficulties were reported. Some of these are paid snow-surveyors, though their interest and cooperation were enlisted before remuneration was even mentioned. Others are employees of either the Dominion or Provincial Governments (forest rangers, park wardens, etc.), and they have undertaken the work from pure interest, and without cost to us, care being taken that no pressure was brought to bear on them from heads of their departments. Two hydroelectric power-companies and a pulp-company also cooperate at no cost to us. The Columbia Basin System is therefore now launched I feel, under good auspices.

The Powell River Company (pulp and paper) of Powell River, British Columbia, who, as I reported last year, initiated snow-surveys on its watersheds under our guidance, has now asked us to take them over officially and handle them with our other systems. This we have gladly done, since it assures standardization and the application of any improvements in technique. The Company will continue to maintain trails and shelter-cabins, keep them stocked, and supply transportation and assistants.

Midwinter (end-of-January) samplings are now taken on two key Okanagan courses, and next winter I intend to obtain end-of-January and end-of-February samplings on a number of key Columbia Basin courses. The data they will afford should be more valuable than is the case farther south, on account of the undoubted heavy snow-loss from evaporation during February and March--particularly in years of strong Chinook winds.

## Oregon

(a) March 1 (J. H. RYAN)

Slightly more than 100 snow-courses now comprise the snow-survey network in Oregon. During 1938 this network was rounded out by the addition of courses where experience had shown their need. Additional shelter-cabins have been provided in the Blue Mountain Area of Eastern Oregon. Also, this year has seen a considerable increase in the number of snow-courses at which measurements are made each month, and the additional information appears to be well worth while.

The demand is steadily increasing for reports on snow- and weather-conditions in the recreational areas. As a result this information is being broadcasted and printed four or five times a week for the Mount Hood and Crater Lake areas, and is released once or twice a week for the less-important recreational areas.

A goodly portion of this winter's snowfall has occurred after February 1, and the measurements of March 1 are showing densities as low over the entire State. Sample tubes are bringing up frozen ground at many stations. Rain fell on most of the watersheds in late fall. These measurements and reports indicate an early runoff, with a rather scanty water-supply during the summer for those areas which depend on direct flow of the streams. Nearly all the reservoirs have a heavy carry-over of water stored in 1938 and will be in good shape this year.

(b) April 1 (R. A. WORK)

Lacking the extended records on which accurate forecasts must be based, but believing that information accumulated to date is of value in forming general estimates of prospective water-supplies for Oregon in 1939, a series of water-forecast-committee meetings were held in important irrigated regions of Oregon for the fourth consecutive year during the period April 5 to 12, as follows: Medford for southern Oregon; Bend for central Oregon; Burns for eastern Oregon; Union for northeastern Oregon; Hermiston for the Umatilla-Walla Walla River-Basin and Portland for the Columbia River-Basin, embracing drainages in seven States and British Columbia. Most of the cooperating agencies were represented at those round-table discussions.

Measurements throughout the Cascade and Coast Range mountains show that snowfall was nearly normal on March 1; but since early March, snowfall at the higher elevations and rainfall in the valleys have been far below normal. Consequently, on April 1 snow water-content on nearly all snow-courses on various southern Oregon stream-basins was below normal.

Although snow water-contents on some watersheds are the lowest since 1934, expected stream-flow may not be decreased to the low points of 1934 because of the fact that watershed-soils were so well primed in 1938 that a favorable hold-over effect will exert some influence in maintaining stream-flows this year above extremely low level.

The growing season is well advanced over normal and although that may result in little difference in dates of harvest for grains and grasses, it is expected to advance the date of harvest of fruit and bulbs. Consequently, this will tend to offset in some degree the anticipated late-season water-shortage.

Low-elevation ranges from present indications will be short this year unless heavy precipitation comes soon. Because of rapid retreat of the snow-cover to a relatively small area at the higher elevations, larger watershed-areas are now exposed to early summer drying more than usual and this factor compounded by heavy breakage of timber by snow last year is expected to result in a hazardous and long-extended fire-season.

In central Oregon an unusually extended and more troublesome fire-season is anticipated by foresters because of the exceptionally early recession of snow-cover to higher elevations and the hold-over of above normal growth of grasses last year.

Water-supplies in the Hood River Valley are expected to be as good as usual.

## California (HARLOWE M. STAFFORD)

Very unusual weather was the order of things in California during the winter of 1937-38. A winter that got off to a good start both as regards rain at the lower elevations and snow in the mountains, received a heavy setback with the storm of December 9-11, 1937, when a freak rain occurred throughout the Sierra, melting away all prior accumulations of snow up to the 9000-foot level and causing disastrous floods in the low country. Late in December a little snow fell, but up until the end of January, in spite of a surplus of early precipitation, the snow-pack in the mountains remained below normal. At the end of January it began to snow in earnest and for a period of two weeks, great quantities of snow fell each day. During this period occurred the great wind of February 8--which caused so much damage in northern California--and the third week of March helped to swell the snow-pack, so that at the end of the season, in spite of its late start, the snow-pack was far above normal.

An all-time high record for measured water-content in California was recorded this year at a Mount Lassen snow-course where the snow-cover reached a depth of 282 inches with a water-content of 152 inches.

In the interests of more accurate forecasting, several new snow-courses have been added during the past year. The number of snow-courses in California is now very nearly 200.

The snow-conditions for 1938-39 are the opposite of those of 1937-38. Fred H. Paget, in charge of the California Cooperative Snow-Surveys, reports that for the Sierra Nevada as a whole there is about half a normal pack, the lightest in five years. As noted at the beginning of this report, a warning has been issued to conserve to the utmost all impounded water-supplies.

Fortunately reservoirs on the eastern slope of the Sierras serving Nevada are well filled. Los Angeles reports that the ground-storage in the Owens Basin and carry-over from last year in surface-reservoirs, preclude any possibility of water-shortage, regardless of deficient snowfall this winter.

Tahoe Tavern is announcing the scant snow-cover and resulting warmer winds as an inducement to visit the Lake earlier than usual.

Conservation (JOSEPH KITTREDGE, JR.)

Because of a sabbatical leave this year, I have been away from Berkeley much of the time and have temporarily discontinued the snow-project. Consequently I shall not have anything to report this year, but expect to have something again next year.

## Snow-sports, transport, and avalanches

The earlier title of "Snow-sports" has been expanded to "Snow-sports, transport, and avalanches," so closely related are the three.

### (a) Snow-sports

Because of the unprecedented trek of the population to the snow-fields, the physics of snow has found very practical application. With this trek have grown systems of forecasting of weather, road-conditions, and snow-surface. The National Parks and Forest Service has made snow-sports one of the major features of its programs. The Bureau of Agricultural Engineering has established a winter weekly radio forecast-service in the western States and the Weather Bureau has developed a system for New England. The Yankee Network is maintaining a sports-service from Boston.

The National Water-Resources Committee is preparing a report on a uniform nomenclature of snow.

The need and development of such uniform nomenclature is vividly set forth in the following report by Bestor Robinson, Chairman of the Winter-Sports Committee of the Sierra Club and one of the representatives of snow-sports on the Committee on Snow:

"As a result of the veritable flood of skiing accidents which threaten to hamper the development of the sport, numerous programs have been developed for the reduction of skiing accidents and the rendering of effective first aid, so as to minimize the resulting injuries.

"I think that the greatest progress has been made spontaneously. There is hardly a ski-club in the United States which, by one means or another, does not emphasize the necessity of safety in skiing. In skiing centers signs are posted and the National Park Service and the National Forest Service, by pamphlets and by posters in appropriate areas, are doing their full share of this work. Although there are numerous detailed safety-rules, the essence of all of these programs is the development of a public opinion among skiers insisting upon skiing under complete control.

"The national and divisional ski-organizations, through appropriate committees, are doing excellent organizational work to further this aim, although I believe the spontaneous developments, which I referred to above, are most effective.

"Because of the rapidly increasing number of skiers, it is difficult to determine whether the skiing-accident rate has been reduced. It is the general prevailing opinion, however, on the part of most of those familiar with the situation, that the accident-rate is down, although the number of persons injured is still on the increase.

"With regard to first aid to skiers, effective organizational work has been done along various lines. The American Red Cross, in cooperation with the National Ski Association, has just completed a winter-sports first-aid booklet which has been well received. Numerous ski-clubs are undertaking the education of their more active members in first aid, with particular reference to skiing accidents.

"A splendid development has been undertaken and is being vigorously pressed by the National Ski Association toward the organization of ski-patrols, consisting of qualified persons who will undertake the responsibility of leadership in first-aid work whenever a skiing accident occurs and actually organizing patrols in connection with ski-meets. On the whole, it appears that the problem of skiing accidents is being effectively met.

"Skiers owe a debt of gratitude to the experts on snow in the development of nomenclature of snow-conditions (not uniform, it is true, but approaching standardization). Not only are reports describing the condition of snow in particular centers becoming intelligible, but the conversation of skiers is rapidly adopting the generally accepted descriptive terms which have resulted from the comments and criticism directed largely by members of the Committee on Snow. This deliverance from a confusion of terms is a substantial contribution to the sport.

"I have been very much interested in the fact that much of the work done by members of the Committee in describing the different types of snow and the method of formation of the same has worked its way into the skiing fraternity. One frequently hears around the fireside prolonged talks with regard to the conditions which produce types of snow most desired or, on the other hand, most detested by the skiing fraternity. There are discussions about waxes in which a surprising amount of technical information comes from the minds of sportsmen without a formal scientific instruction in such matters. The fact that this body of information is seeping down from the scientists to the sportsmen not only makes sport more interesting but actually aids in the solution of the everyday problems of the skier of what waxes to use, what snow to travel on, where to find the best snow, and how to avoid avalanches."

(b) Transport

The snow on Western trans-mountain highways has been too shallow the past winter to cause any difficulty or attendant problems. Also avalanche-hazard has been low.

### Equipment

The improvement of equipment continues to be a leading topic of discussion at all conferences and is reported in detail in the Proceedings of the Snow-Survey Conferences at Los Angeles and Spokane ("Transactions for 1939," Part I, pp. 71-79 and 135-136.)

An unsolved problem is the adhesion of snow to the duralumin metal of the sampler-tube and spring-balance staff. Jewett Schrumn is investigating metals, while John T. Ryan is testing enamels.

George A. Lewis submits several suggestions as follows regarding treatment of equipment, climbing accessories, and protection from snow-burn:

"With regard to the suggestions on snow-surveying which you requested, I shall confine my remarks to a few points which we have now found from experience to be of value.

"In the past, we depended upon different waxes and their proper application for aids in climbing steep slopes. Sealskin-climbers were of course highly successful, but their cost was rather out of proportion. We have now found that ordinary deerskin, stretched, dried, and cut in proper dimensions can be made into climbers of this order that are the equal of the best sealskins. The cost of such home-made climbers is very reasonable.

"Frequent use of the cleaning knife results in small indentations in the lower edge of the sampler-tube slot. These are rather difficult to remove without special tools. Two short blocks rounded to fit the inside contour of the tube and fastened to a length of rod will do this work nicely. Wrap a piece of emery-cloth around the blocks and place a short length of coil-spring between them to hold the blocks firm in contact with the walls of the tube.

"Ski storage-racks, especially where hot summers prevail, must be so designed as to hold the ski in a true horizontal, as well as a vertical plane. We recently built such a rack and because of its advantages over the old type, I offer it here. The rack is nothing more than a series (we use four) of short-legged tables constructed with a top two inches in thickness and four-inch by four-inch timbers for legs. The tables are set one atop the other.

"The skiis are placed face down on this flat table-top and are held rigidly in place with a cross-bar at each end. A block is shoved between ski and table at the center to give proper curvature. A brace is also placed under the top of the ski to insure correct turn-up. The ski is thus held firmly in proper shape and cannot warp in any plane. This rack is also useful for reforming old skiis after they come from the steam-box.

"I am anxious to report our successful use of a new (at least to us) sunburn-treatment. We tried it for the first time this year and heartily endorse it. This preparation is known under the trade name of Kip-Tannic, and while it is not advertised to the laity, it can be procured from the Kip Corporation, Ltd., in Los Angeles. As a treatment, it is best we have found and we also used it successfully as a preventive."

### Polar activities for 1938 (LAURENCE M. GOULD)

(a) Arctic--Soviet Russia has accomplished more arctic work in the past few years than all other nations combined. Only such experience could have formed sufficient background for completion of the drift of the four men of the Soviet North Pole Party. Two aspects of this achievement stand out: (1) The excellence of the equipment, much of which was specially designed; and (2) the great amount of scientific work which was successfully completed. This achievement takes its place with the greatest that have preceded it.

One gathers from the press that several arctic parties were sent out during 1938, but since there has been no announcement from the Arctic Institute at Leningrad, it is impossible to evaluate their achievements.

Among other nations carrying on explorations in European arctic regions, the following expeditions were completed during 1938: Cambridge Spitzbergen Expedition which accomplished important research chiefly in geomorphology; the Norwegian Expedition to Svalbard under the leadership of Hoel which carried out important aerial surveys as well as a comprehensive program of research on the ground; an expedition from the Imperial College of Science in London consisting of ten members carried out a most comprehensive scientific survey of Jan Mayen.

Greenland was the scene of much activity from a variety of nations. Lauge Koch continued his able investigations with important flights over Peary Land and adjacent areas of the northeast coast. In addition, Koch's East Greenland Expedition, which began in 1936, completed its important geological work from four different stations.

Miss Louise A. Boyd continued her arctic work with an expedition along the coast of east Greenland. Four Norwegian expeditions likewise visited and did work at different places on the east coast of Greenland. Still another expedition had east Greenland as its place of attack in 1938, namely that of the Academic Alpine Club of Zurich which, among other things, ascended Mount Forel.

No less than ten expeditions were at work along parts of the west and southwest coasts of Greenland, among them being the Oxford University Greenland Expedition, the Cambridge West Greenland Expedition, the Danish Geological Expedition to Northern West Greenland, and the American Meteorological Expedition (1937-38) under the leadership of MacGregor.

Eight expeditions carried on work in the Canadian Arctic, Baffin Island being the principal region of study. The British Arctic Expedition (1937-38), Bentham Expedition (Ellesmere Land, 1936-38), British Northern Baffin Island Expedition (1938-39), and the Swiss Ethnological Expedition (1938-39) were among them.

Intense activity in the arctic region has no counterpart in antarctica during 1938. The R.R.S. Discovery II and R.R.S. Scoresby continued their oceanographical work with chief attention directed to the study of the distribution and habits of whales. Lincoln Ellsworth made his fourth antarctic expedition aboard the Wyatt Earp with two planes. Flights were made inland over the Enderby Sector.

A more detailed record is given by Raye R. Platt under the title "Recent exploration in the Polar Regions" [Geog. Rev., 1939, pp. 303-309]. The following excerpt is given because of its similarity to the planned polar drift of Nansen in the more famous Fram (Forward):

"The most recent soviet exploit in the arctic, and one that may be more important than any of the others in contributions to knowledge of arctic meteorology and oceanography, is the result of an accident. Late in 1937 the ice-breaker Sedov was caught in the ice in latitude 78° 10' north and her propeller was broken. Drifting northward for more than a year the ship reached 85° 29' north and then drifted westward near the 84th parallel for some months. Early this year the drift northward began again, and by March 3 the ship was at 86° 20' north, 35' north of the Fram's farthest north. Originally it was thought that the ship might drift over the Pole, but now it is believed that she will reach about 87° north and then follow the course of the North Pole Drift Expedition."

## Snow-survey conferences

The Western Interstate Snow-Survey Conference is now firmly established and is gradually taking the regional form of the Section of Hydrology, with which it has decided to work in close though informal cooperation. Through the cooperation of 20 organizations--Federal, Provincial, State, municipal, and private--who either aided in publication or purchased reprints, a circulation of 2500 copies of the "Proceedings" of the Davis Conference was made possible.

During December, 1938, two further conferences were held: One at Los Angeles and the other at Spokane, in affiliation with the regional meetings of the South Pacific Coast and the North Continental Divide areas. At the latter meeting, the program was joint and confined exclusively to snow- and runoff-problems.

The following themes were discussed at Los Angeles [see "Transactions for 1939," Part I, pp. 53-96].

(1) Snow-surveying
  Status of proposed bulletin on principles and practices of snow-surveying, by James C. Marr
  California Cooperative Snow-Surveys: Directions, suggestions, and hints for snow-surveyors, by Fred H. Paget
(2) Forecasting stream-flow
  Improvements in the methods of forecasting stream-flow, by Carl Elges
  The use of precipitation-gage measurements in forecasting the inflow to Lake Mead, by O. C. Reedy
  Need of higher-level snow-survey courses in the Colorado River Water-Conservation District of Colorado, by F. C. Merriell and M. C. Hinderlider
  Arizona viewpoints, by Jesse C. Wanslee
(3) Improvement of apparatus
  Anodyzing or hardening the surface of snow-samplers, by James C. Marr
  Improvement in Mount Rose spring balance; "tickling" corky snow, by Fred H. Paget
  Paraffin versus enamel; optimum number of sampling points; improvement of tubular balance, by Fred H. Paget

(3) Improvement of apparatus (continued)
   Method of applying bakelite to snow-sampler, by Wayne Poulsen
   Applying the Chatillon iso-elastic springs to the Mount Rose spring balance, by Carl Elges
   Shielded storage precipitation-gages, by Ashton R. Codd
(4) Snow-sports
   Snow-surfaces in the high Sierras for skiing purposes, by Wayne Poulsen
   Skiing in Southern California: Essential equipment, by R. C. Youngquist
   Outline of Weather Bureau Northeast States Winter-Sports Service, by Merrill Bernard
   Snow-activities of the National Park Service, by R. D. Waterhouse
(5) Progress and policy
   Progress-report of Western Interstate Snow-Survey Conference, by H. P. Boardman, Chairman, Executive Committee

At Spokane the following symposia were presented and discussed:

Symposium 1--The limit of practical usefulness of snow-surveys made in headwater-regions when used for predicting runoff at localities quite removed from courses
   (1) Fort Peck Reservoir, by D. B. Freeman
   (2) Northern Rocky Mountains, by H. T. Gisborne
   (3) Smaller watersheds, by J. P. Bonner
   (4) Correlation of headwater-streams of North Continental Divide, by O. W. Monson

Symposium 2--Effect of soil-priming by fall precipitation on spring runoff
   (1) Upper Snake Basin, by James C. Marr
   (2) Analysis of snow-cover and runoff in Upper Snake, Upper Yellowstone, and Swift Current watersheds, by O. W. Monson
   (3) Relation of fall stream-flow to spring runoff, by Henry C. Eagle
   (4) The influence of autumn rainfall on the runoff from melting snow, by R. C. Farrow

Equipment
   Construction of snow-survey shelter-cabins, by R. A. Work and R. L. Parshall

## Publicity

Interest in snow-surveying has made remarkable strides in recent months. The effort of the Bureau of Agricultural Engineering through Blaine Stubblefield finally bore unexpected fruit in "Snow-surveyors of the high Sierras" in Reader's Digest [March, 1939] and an expanded article on "How much snow" in Scientific American [March, 1939]. These are to be followed by a dramatic presentation of snow-surveying in color photographs by American Magazine in the early winter of 1939, and a map of watersheds and forecasted runoff with snow-survey scenes by Life at the time of the national snow-surveys in April, 1939.

Movies in color in the Tahoe Area have already been made by Walter Herz and Frank Whitman Wilson. The movie by the Los Angeles Department of Water and Power is being rejuvenated.

Views of unusual brilliance have been published by the California Cooperative Snow-Surveys in California Highways and Public Works for May, 1938, and April, 1939. Some of these appear in California Monthly for January, 1939. R. A. Work, Bureau of Agricultural Engineering, has prepared pictures of the Oregon shelter-cabin with its tower-entrance.

To these must be added the detailed radio and printed broadcasts by various organizations and the succeeding publication of snow-survey data by the Weather Bureau and the Bureau of Agricultural Engineering for reference and research.

Interviews by the United Press and Associated Press have been sought and given. The final result will be helpful.

A more formal effort has been made by R. C. Farrow in a paper on "Snow-surveys: A new medium for forecasting runoff" written for the Engineering Institute of Canada and published in The Engineering Journal [October, 1938]. It is based on conditions obtaining in British Columbia. Mr. Farrow comments as follows:

"The history, technique, and possibilities of snow-surveying are very little known in Canada in general, and the article was intended to try and awaken the interest of the engineering profession and of industries or organizations to whom they might be of value. In this there was some measure of success; I received several letters from engineers in different parts of Canada--mainly evincing interest, but others asking for further information. The Pulp and Paper Magazine, the organ of the pulp and paper industry in Canada, asked permission to reprint the article in its December issue. This was granted; and the widened circulation brought letters from the engineers of two eastern pulp companies, asking for further information and from whom they could purchase snow-samplers.

"I also received a letter, which was quite the most gratifying of all, since a purely technical article had reached out and contacted a small lumberman in a remote settlement and enlisted his support. This man evidently runs a small logging operation on the Arrow Lakes (Columbia River) and probably casually read the article while waiting in the office of the nearest mill. He wrote enthusiastically, asking if it would soon be possible to give forecasts for the smaller streams as well as the large, as spring runoff was a matter of great concern to him and his kind, and that if I wanted to put in a snow-course anywhere in his vicinity, he would gladly 'look after it' for me, adding that 'of course' he would not expect remuneration, as he would be only too glad to cooperate."

W. W. McLaughlin, Chief, United States Division of Irrigation, is now planning a series of state-maps to accompany the printed broadcasts of water-supplies. These maps will provide for each watershed a statement of (1) the percentage of snow-cover April 1, (2) the water in storage, and (3) the probable water available for late crops. Thus a complete picture will be given of the seasonal assets for irrigation-use by the rancher in planting crops and by Federal agencies in making loans.

## Research

Since 1935, urgent recommendation has been annually made for an increase in the Congressional appropriation to carry on research projects essential to improvement in stream-flow forecasting. The present appropriation is only $15,000. It should be three times as large. The wide publicity already active should give snow-surveying a national standing.

The National Water-Resources Committee is now pressing forward (a) the development of a uniform nomenclature of snow and (b) the standardization of snow-survey and forecast-methods.

A series of charts showing the close relationship between measured snow-cover and streamflow over a long series of years and for widely distributed watersheds has been compiled in connection with plans for the operation of flood-control reservoirs.

The individual research-problems can best be grouped topographically:

### Newfoundland--Well-measurements (ERIC HINTON)

Last year it was proposed to install a number of four-inch pipe-wells at various points in the watersheds, for the purpose of determining the ground-water levels. The work was not done, so it is recommended that the wells be installed during the present year. The condition of ground-water level is known to affect the flood-runoff.

One of the difficulties in forecasting the necessary volume of spilling is our inability to forecast the date that the spring flood will commence. Experiments conducted in Russia indicate that this factor may be influenced largely by soil-temperature. It is recommended that this phase of the subject be studied and if possible some experiments conducted here during next winter.

### Canada--Snow-resistance of aircraft skis (GEORGE J. KLEIN)

During the past three winters we have tested half-scale model-skis at Ottawa, Ontario. The results have shown that considerable improvement in the snow-performance of skis can be obtained by the proper choice of ski-shape, material, and unit-loading. However, due to weather-conditions at Ottawa, we did not obtain sufficient number of tests at low temperature.

We are continuing the test this winter at Sioux Lookout, Ontario, where sub-zero weather is quite common. These tests will be carried on for at least another month.

This winter, a number of aircraft-operators in northern Canada have been using highly loaded bakelite-surfaced skis as recommended in the paper "The snow-performance of aircraft skis." These skis have shown their superiority over the usual metal-surfaced skis both in their snow-performance and resistance to wear.

Some of our newer ski-models have been surfaced with bakelite containing other materials as graphite. So far this winter, the tests of some of these skis have been very promising.

### New England

(a) Snow-samplers and reduction of ice-cover (PAUL L. BEAN)

We are this year testing the new Government snow-sampling tube alongside of the standard tube used for many years. In general, the new tube is giving results smaller than obtained with the standard tube. Final results will not be available for purposes of study before May 1, 1939.

We are also studying the samples of snow with a magnifying glass, to determine snow-characteristics and to study the changes in characteristics as the season advances. Vertical cross-sections of the snow-cover, about six feet long, are being exposed and studied to determine possible variations in density and to establish facts as to where and how many readings should be taken at a given station to get a fairly representative sample.

To determine the effect of the diameter of the sampler-tube on the water-content of the sample, specimen cores are being taken with the new Government tube, the standard tube, and tubes of six-inch, nine-inch, and twelve-inch diameter.

We also procure daily readings of water-content of the snow at one station, also all other meteorological data usually gathered by the Weather Bureau, and furnish the same to the Weather Bureau in Washington. We now have six years of continuous daily records of water-content of the snow during the time a snow-cover exists. It is our purpose to compile a report on results of these daily records in the near future. We now believe that such a record gives very accurate data on which to base storage-operations.

Our knowledge of the water-content of the snow in the Androscoggin River Valley in Maine has made possible a river-operation never before attempted. Knowing from the water-content that we could fill our storage-capacity, we have been, since March 1, releasing stored water in heavy volumes to reduce the ice-cover in the River, which was heavy enough to be a menace. This has resulted in completely clearing nearly 75 miles of the River before the spring break and reducing the remaining ice-cover to a thickness which is no longer a menace. The operation has been very satisfactory.

(b) Ice-jams (H. K. BARROWS)

At the present time I am much interested in the subject of ice-jams and their causes and am making some study of it in connection with one or two pending matters. I hope some time to be able to prepare something that will be of interest in this field.

New York--Measurements with large and small tubes (ARTHUR W. HARRINGTON)

The two following measurements were made in the St. Lawrence River Basin with the regular Adirondack snow-sampler, and at the same location a simultaneous measurement was made with the small Friez tube. The measurements are noted as made with "large" or "small" tube.

| | | | | | |
|---|---|---|---|---|---|
| March 9 | U.S. Geological Survey | Tupper Lake, large | 16.05 | 4.38 | 0.273 |
| | | large | 16.6 | 4.56 | 0.275 |
| March 8 | U.S. Geological Survey | Childwold, large | 17.5 | 4.68 | 0.267 |
| | | small | 17.35 | 4.58 | 0.267 |

Utah--Ground storage; rate of melting (GEORGE D. CLYDE)

We are continuing our research-work on the effect of ground storage-conditions and on the effect of the rate of melting.

Alberta--Comparison of Mount Rose and Duralumin Sampler (O. H. HOOVER AND W. T. McFARLANE)

For the survey of 1939 it was noted that the snow on all courses consisted of a distinctly granular texture but was noticeably more settled than during the surveys of 1937 and 1938. A prolonged Chinook lasting from March 18 to 24 is believed to have reduced and settled the snow-cover. The Mount Rose and improved aluminum snow-samplers checked very closely, one against the other, but the new tubular scale with the aluminum sampler is distinctly superior for speed and accuracy over the Mount Rose balance No. 407 as formerly used in this area.

British Columbia--Spring field-moisture deficiency; intermittent melting (R. C. FARROW)

(1) Projects, under way or planned

In so far as the project I suggested to Dr. Bowie's Planning and Project Committee is concerned (Farrow project No. 3), this may be divided into two general parts: The first, deals with the relationship of accumulated records of snowfall to runoff; the second, relates to a study of the effect of autumn rains on spring runoff--that is, a study of spring field-moisture deficiency. I have not had occasion to make further studies covered by the first part. In fact, in proposing it as a project, I had in mind that the method adopted might be tried out in some other area, since my studies were brought to a conclusion in so far as the Canadian Columbia Basin is concerned.

Regarding the second part, I have made some progress in this study, and what I had accomplished up until that time was briefly outlined in the paper I sent to the Spokane meeting of the American Geophysical Union in December, 1938. I intend to continue these studies. It has been suggested that a paper on this subject be prepared for the Washington meeting of the International Commission of Snow, in September, 1939.

As a result of correspondence and discussions with Merrill Bernard, Chief of the River and Floods Division, United States Weather Bureau, we are installing a battery of the Bureau's new shielded snow-gages at Field, British Columbia, in the Canadian Rockies, adjacent to our Snow-Course No. 12.

Ashton R. Codd, Hydrologic Supervisor of the United States Weather Bureau at Salt Lake City, has been giving me every assistance, and has visited Field this winter. Unfortunately, the winter was too far advanced by the time the gages were assembled at Field to make it worth while setting them up for this winter. Their operation in this area, in parallel with the snow-course and regular meteorological station should prove interesting.

Midwinter (end-of-January) samplings are now taken on two key Okanagan courses and next winter I intend to obtain end-of-January and end-of-February samplings on a number of key Columbia-Basin courses. The data they will afford should be valuable for discussion; but as a criterion to runoff-possibilities I am afraid they will be less valuable than is the case farther south, on account of the undoubted heavy snow-loss from evaporation during February and March--particularly in years of strong Chinook winds.

(2) Intermittent melting

I have found it necessary to correct for spring field-moisture deficiency; and now a new distorting influence of enormous effect has suddenly made its appearance. I believe it is due to the long spring which prevailed last year, with protracted and intermittent melting; this would allow more time for evaporative processes to work on the snow and occasion some loss, but also it could allow a large proportion of melting snow to be diverted from surface-runoff into ground-water channels, only to reach the streams months afterwards. If this theory is correct, it should be substantiated this summer by a runoff in excess of snow water-content expectations, by a rise in the ground-water table as indicated by the behavior of wells and by the increased flow of springs. It will be something if I have found an explanation for this phenomenon, but the problem of producing a forecast with any reasonable accuracy when this condition obtains will still remain.

California--Snow-pack-runoff relation-curves (HARLOW M. STAFFORD)

On account of the record snow-pack, all of the forecasts of runoff from the Sierra streams had to be determined by extending the existing "Snow-pack-runoff relation-curves" considerably beyond the limits of any of the established curves which are based upon the data gathered during the past eight years, and being in uncharted territory the tendency was to forecast conservatively.

A check of the historical figures of full natural flow which have since become available shows that on the average the forecasts throughout the Sierra were about 15 per cent low. This would indicate that the curves tend to flatten off somewhat after they pass beyond normal conditions--that is, the excess snow above normal has a greater runoff-efficiency than the amount up to normal.

It was thought for a while that certain deficiencies in the forecasts for 1937, when preseason precipitation was deficient, and the excesses beyond the forecasts for 1938 with heavy rains before the snow accumulated, might lead to an evaluation of the effect of the pre-snow-pack precipitation upon the snow-pack-runoff relation. Studies made of this, however, in several watersheds do not indicate that in the Sierra the pre-pack-precipitation has an influence of more than two or three per cent, and even that is not definite. It is apparent from our studies that without more data no correction can be made for variation in pre-pack-precipitation in the Sierra watersheds.

Forecasts of minimum stream-flow for 1938 at several points along the Sacramento River and its tributaries, together with forecasts of the probable resultant maximum salinity-incursion to the Sacramento-San Joaquin Delta, were accurate to a high degree.

## Our retiring President

Not only as Chairman of the Committee on Snow, but especially as Vice-President, I desire to do honor to our retiring President, LeRoy K. Sherman. He not only saw growth rather than rivalry for the American Geophysical Union in the formation of Regional Meetings of the Section of Hydrology in the West, but he eagerly joined the Committee on Snow and threw his enthusiasm into its development.

The following letters to Dr. Church and Dean Clyde reveal his persuasive personality:

"I hope you will be able to attend the annual meeting in Washington on April 27-28. The Committee on Snow this year, like last year, has been very active. As one interested in hydrology from all of its diversified viewpoints, I have followed with interest and appreciation the work of your Committee and your associates, The Western Inter-State Snow-Survey conferences. One of the most important elements in the development of your work, according to my point of view, is the scientific researches which are leading to a very definite determination of the snowfall-runoff relation and our ability to consequently make better forecasts. May I add that a part of this successful development has been due to the inspiration of the Chairman of the Committee on Snow."

"Thank you for sending me your April 1st Bulletin on water-supply forecast. This is an excellent demonstration of the practical value of application of the science of hydrology. I am impressed with the rapid progress that has recently been made in forecasting runoff from snow-surveys."

## International

The International Commission of Snow is merely the Research Committee on Snow grown geographically and scientifically broader, for it embraces practically all fields of snow and ice with their various manifestations from snow-cover to avalanches and from underground ice to icebergs. Its membership embraces 28 countries and approximately 172 persons.

Originally its triennial program was restricted to three questions to insure careful investigation and final conclusion at the following Assembly. However, as in the American Geophysical Union, it was found desirable to supplement selected topics with general papers of immediate or special interest, thus satisfying all types of membership.

Such is the joint program of the Commissions of Snow and Glaciers now in preparation for the Seventh International Assembly, September 4-15, 1939. The general outline of this proposed program is as follows:

### Special conferences

Uniform nomenclature of snow-cover
Standardization of snow-surveying
Classification of international bibliography of snow and ice

### Discussion of questions

Question 1--The permeability of snow and its retentive capacity
Question 2--The influence of snow and ice on the flow of streams
Question 3--Snow-maps of the world

### General papers

- (I) Snow-cover
  - La Distribution de la Neige en Italie
- (II) Forecasting stream-flow
  - Effect of soil-moisture on runoff
  - Forecast-factors in Australia
- (III) Runoff
  - The relative and seasonal value of glacial streams for irrigation and power
  - Relation of snow and ice to floods
  - Effects of Chinook (Föhn) winds on snow-deposition and redeposition
  - Effects of Chinook (Föhn) winds on snow-cover and runoff
- (IV) Lake and river ice
  - Supercooling of surface-layer of open water
- (V) Transport
  - The snow-resistance of aircraft-skis
  - Frost-action in soils
- (VI) Physics of snow and ice
  - Evaporation from snow
  - Evaporation and melting of snow at high altitudes
  - Snow-melting in spring time
  - Snow-melting computed by the energy-equation
  - Accelerated evaporation of ice
  - The evolution of snow to firn
    - (a) Alpine evolution
    - (b) Arctic and sub-arctic evolution
  - Joint report of scientific results of snow-researches at Davos and Weissfluhjoch
  - Latest investigations on snow and ice of the Soviet cryologists
  - Bericht über deutsche Schneeuntersuchungen
- (VII) Avalanches
  - Report of the Swiss Snow and Avalanche Commission
- (VIII) Glaciers
  - Question I--Studies of the variations of size of glaciers
    - (a) Grössenschwankungen der Gletscher in Island
    - (b) Gletscherschwankungen in den deutschen Alpen
    - (c) The last advance of glaciers in the Coast Mountains, British Columbia
    - (d) Variations of glaciers in the continental United States and Alaska, 1933-38
    - (e) General report on Question 1
- (IX) Icebergs
  - Icebergs: Their drift into the north Atlantic and protective measures
  - De la Destruction des Icebergs

(X) Recent expeditions
  - Wordie Expedition to northwest Greenland and Arctic Canada
  - Snow-experiences on Nanda Devi and Mount Everest

(XI) Apparatus
  - Seasonal recording gages
  - Seasonal protected gage of the United States Weather Bureau
  - Iso-elastic springs
  - Problem of adhesion of snow
  - Exhibit of equipment

(XII) Program and policy
  - Report of Special Committee on Questions for 1942
  - Personnel
  - The News-Letter
  - Bulletins

This International Assembly will afford an early opportunity for the members and friends of the Committee on Snow to show through attendance and hospitality their appreciation to their foreign colleagues for having generously authorized the organization of the Commission of Snow in response to the development of snow-surveying and the request of the American Geophysical Union that the International Association of Scientific Hydrology give it recognition.

## Summaries of leading publications

Because of the public interest in the forecasting of precipitation-trends, the paper by Ernst Antevs on "Rainfall and the tree-growth in the Great Basin, 1938" has been selected for analysis. The following letter (March 22, 1938) from the Chairman to Dr. Antevs is quoted as of interest:

"We have been greatly interested in reading your special publication on 'Rainfall and tree-growth in the Great Basin.' It was first called to our mind by a news-note stating that you had forecasted a drought in the Western Great Basin for the next ten years. That naturally sold several copies of your work. Your conclusions bear no such threat. Rather they are fully in line with research done several years ago by the Department of Meteorology, of the Nevada Agricultural Experiment Station, on the frequency of low levels in Lake Tahoe. The specific problem given us by the Sierra Pacific Power Company was the determination of the frequency of the fall of Lake Tahoe below its rim during the next 50 years with present regulation. On the basis of past 50 years, computed from the rainfall-records at Colfax and Nevada City, it was determined that Lake Tahoe would fall below its level once every ten years and sometimes twice during such period. Our experience is bearing this out and seems to be fully in keeping with your own conclusions.

"It is noted that the 'cycles' you mention are irregular with curves superimposed upon longer trends. This again is in accord with the views of George V. Sager, Meteorologist, United States Weather Bureau, Reno, Nevada, who has written a paper on 'The long-term trend of rainfall in the Central Sierra Region.' His study indicates that the trends are local as between the Central Valley of California and the Wasatch Region of Utah. Indeed, during the present season we have had an unusual example of precipitation in the Sierra Nevada, double in relative amount to that in the Humboldt River Basin, Nevada. Word came from Utah that the streams of Northern Utah will probably be normal this season, but from Montana word comes that the runoff will be only slightly better than a year ago when extremely low water was experienced. Trends are made up of such a complex of meteorological factors that it is questionable whether anything approaching a recurrent cycle can be found. The very heavy snowfall in the Sierra the present season seems to be due to a succession of steep depressions reaching far south and causing abnormal precipitation. Indeed, in January when precipitation is heaviest there was a long period of fair weather, as I recall it, preceded and followed by very heavy storms. Mr. Sager's article is in 'Proceedings of the Western Interstate Snow-Survey Conference' of February 18, 1933, copy of which is being sent you.

"Your study is a most valuable gathering of data and research with a viewpoint and conclusions conservative and forward looking so far as meteorological data at present permit."

### Rainfall and tree-growth in the Great Basin, 1938

(Review by George V. Sager)

Dr. Antevs first presents the data of precipitation, runoff, lake-levels, and related phenomena for each of five regions in northeastern California, south-central Oregon, northern Nevada, and northern Utah, comprising the northerly portion of the Great Basin, using all sources of possible information to supplement actual measurements of precipitation- and runoff-data and to determine as accurately as possible the conditions in the years preceding instrumental records. He then compares the data for these regions and discusses the main rainfall-fluctuations and their significance. In succeeding chapters he discusses factors of tree-growth and details of studies he made of tree-rings at Susanville, California, and Lakeview, Oregon, in 1931, correlating these data with the records of precipitation, runoff, and lake-levels.

In his chapter on the main rainfall-fluctuations he makes predictions of future precipitation based on the smoothed curves of previous precipitation.

The various chapters give evidence of painstaking efforts to collect data from all available sources, and the discussions of the data and their significance show careful thought and accurate reasoning. His conclusion that, owing to differing topography and location relative to storm-tracks, each sub-area has its own distinctive trends, is in full accord with the results of a study made by the reviewer of rainfall-trends in the central Sierra Nevada and across northern Nevada to the Salt Lake Area.

His discussion of the factors other than seasonal precipitation which affect tree-growth is particularly illuminating, showing that in exceptional cases of poor seasonal distribution, or other unfavorable circumstances, the size of the tree-rings is not a dependable index of annual precipitation.

In the opinion of the reviewer, however there is no proper scientific basis for the methods used in attempting to forecast precipitation-trends for a few years in the future. In the first prediction, sections of the smoothed graphs of all the regional-summary plots after 1886 are used.

These sections are superimposed and the mean taken. The third section, being six years shorter than the others, is extended from 1934 to 1940 by the weighted average of the two earlier curves.

In the second prediction, three 16-year sections of the combined graph, somewhat similar in trends, are superimposed and the average curve is drawn. Starting with the termination of 1934, the end of the last curve, this average curve is repeated as a forecast of the probable trend for the succeeding 16 years.

In making the predictions, sections of the combined graph after 1886 only are used, the earlier portion 1868 to 1890, described as a "climax interval," not being considered "because it differs from the comparable later ones in its longer duration and in having two secondary maxima." But if the earlier portion of the graph is based on equally reliable data, is it not as likely to be repeated as any later portion? Is it not at least equally probable that after a certain type of graph has been repeated three times, the trend will be along different lines? The trend from 1868 to 1890, it appears, has not been repeated, and knowing the irregular manner in which wet and dry years alternate in this region--the number of each in succession varying from one to seven--it does not appear that the assumption of the approximate repetition of any particular section or sections of a precipitation-graph is a reasonable basis for a forecast of a future trend.

Aside from the doubtful value of the predictions, the book is entitled to high praise as representing a painstaking collection, compilation, and discussion of a vast amount of widely scattered climatological data; their assembly into a coordinate whole is a distinct addition to our knowledge of the factors of tree-ring growth through the studies of such growth in the Susanville and Lakeview areas.

## Current publications

The list of current publications, usually included in the Annual Report of the Committee, is published elsewhere in these "Transactions" [see pp. 617-635], as this list could not be completed until some time after the submission of this report on April 30, 1939.

## Recommendations

The following recommendations have been presented by R. C. Farrow and have the full approval of the Chairman. They are based on intimate and discouraging experience:

"I presume the idea has been canvassed and probably discarded on account of expense, but the circulation of papers at least to the members of each appropriate committee well in advance of each meeting would add enormously to the value of our meetings, by giving a chance for considered and intelligent discussion. Members unable to attend could send in written discussions. I have thought that the lack of discussion on papers presented at our meetings is a great weakness. It detracts greatly from their value, as, in fact, the discussion is sometimes more valuable than the paper itself.

"Many papers presented are sufficiently abstruse to require careful study before they can be discussed, and therefore no discussion on them is ventured at the meeting.

"This leads to another consideration, and that is that our programs are generally so congested that there is barely time enough for the reading of papers let alone any discussion. If the membership had a chance to read the papers to be presented prior to the meeting, they could be read in outline and still be intelligible to the hearers, which again would leave more time for discussion.

"I am sure most of us contributing papers would be willing to supply up to say 25 mimeographed copies for advance study, unless elaborate diagrams or maps were necessary."

## Appreciation

To the 20 organizations which have supported the publication of the "Proceedings of the Snow-Survey Conference" and particularly to the Nevada Agricultural Experiment Station, great appreciation is due for the growth and extension of interest in snow and its problems and the publication and distribution of this Report. In addition, the latter and its Division of Meteorology have maintained the clerical and editorial work.

Nevada Agricultural Experiment Station,
Reno, Nevada, April 30, 1939

## APPENDIX A--REPORT ON AN INFORMAL EXPLORATION TOWARD IMPROVED NOMENCLATURE FOR GENERAL USE IN CLASSIFYING FORMS AND CONDITIONS OF SNOW

Brent S. Drane

This report is made to the Committee at the request of Dean Thorndike Saville, Chairman of the Special Advisory Committee on Hydrologic Data established by the Water Resources Committee of the National Resources Committee. It describes an informal exploration into the possibility of adapting the procedure used by the agencies which in increasing number are reporting snow-conditions for use by winter sportsmen, so that the observations may secure data of hydrologic value. The undertaking was stimulated by the information brought together at the Western Interstate Snow-Survey Conference at Davis, California, January 8, 1938.

It appeared that the wide variation in terms used in different localities to classify snow-condition constituted a major difficulty and that the most practical approach at this time would be by promoting agreement on a standard nomenclature, which, while equally or more useful to winter sportsmen, will have a basis sufficiently scientific to support its hydrologic application.

Last June, representatives of the Recreational and the Engineering Branches of the National Park Service discussed with the Chairman of the Water Resources Committee their suggestion of a conference of representatives of all interested Federal agencies to that end, and the Chairman accordingly initiated discussion of the possibilities with others, including Dr. Church. Subsequently the proposal was presented in a brief prepared by one of the representatives of the Park Service to a meeting of resident members of the Water Resources Committee's Special Advisory Committee on Hydrologic Data.

Acting upon the advice of that Advisory Subcommittee, the Water Resources Committee later authorized the Subcommittee to aid as a coordinating agency in such an undertaking, its activities to be confined to the reporting services for winter sports and not to be concerned with procedures to convert snow-surveys into runoff-estimates. The correspondence and individual conferences which followed led to the conclusion that adequate response could not be had from the needed number of reporting agencies until the advantages could be demonstrated more clearly through exploratory experiment.

It was believed that in the western winter-sports areas the progression of snow forms was in general relatively simple and the possibility of forecasting changes of condition was relatively high. Moreover, this group recognized the pioneer leadership of a Federal scientific agency, the Bureau of Agricultural Engineering, in developing cooperative snow-surveys and runoff-forecasts, and in reporting snow-condition for winter sports in those areas, and knew that its cordial cooperation in any direction which the exploration might prove constructive could be relied upon.

In the eastern winter-sports areas, on the other hand, it is believed that snow-cover conditions are subject to greater diurnal variations and to wider local variations, more difficult to forecast than in the west; while at the same time skiing has been thus far largely confined to forest-trails which soon become packed by use, rather than extended to cross-country touring as in the west. But the present trend is toward more open-slope skiing and touring, which will require a broadening of the field of reporting beyond the simple "good," "fair," and "poor" which have sufficed to describe conditions on packed forest-trails. It was therefore thought desirable to apply the exploratory process to the eastern snow-sport areas.

It was decided to undertake it informally under a procedure developed by a small interested group consisting of E. B. Ballard and E. F. Preece of the National Park Service, Merrill Bernard and R. E. Spencer of the United States Weather Bureau, Robert G. Stone of the Blue Hill Observatory of Harvard University, Dean Thorndike Saville and Professor A. F. Spilhaus of the College of Engineering of New York University, with your speaker as Secretary to the group.

The procedure is designed to secure a recording of observed snow-condition under each of several of the nomenclatures now most widely used and in parallel with a more elaborate nomenclature designed to reflect more closely the nature of the original snowfall and of its subsequent modifications, together with a record of its history and of its various characteristics at the time of observation as determined by a series of physical tests, and with an expert skier's rating of its skiing condition. The study of a series of such records should disclose certain correspondencies which are consistent throughout most of the record for any particular area; these consistent relationships should indicate the extent to which elaboration of present nomenclature is desirable to convey information needed by winter sportsmen as well as the exactness of definition required by hydrologists.

We believe that it will be entirely practicable to expand the nomenclature used by the observer, and to reduce it to a code-system for telegraphy such that the receiving central agency can immediately condense it into a simpler form which may be required to meet the time-limitations imposed by radio-broadcasting schedules.

The current nomenclatures chosen are the "Carpenter Ski Bulletin" terms (based upon Seligman's classification) as adopted by the United States Weather Bureau, the terms used in radio reporting by the Bureau of Agricultural Engineering at Berkeley, California, and those similarly used by the same Bureau at Denver, Colorado. The newer, elaborated nomenclature is one devised by Robert G. Stone, based upon Seligman's classification. The tests are those proposed by Professor A. F. Spilhaus, of New York University; they are designed to coordinate the nomenclature with the physical properties of the snow and with its meteorological history. New York University, you will recall, maintains a meteorological observatory near Lake Placid, New York.

The experimentation involved in devising the desired report-form delayed its completion until late in the past winter-sports season--too late to afford expectation of any definitive conclusions from its use. When the form was reproduced for trial use, the United States Forest Service was interested to enter also into the experiment. The lateness in the eastern snow-season as well as their limited number of observers near eastern sports-centers led each of the cooperating agencies to submit the form, for prompt trial and comment, to a number of selected observers in their western areas, outside of the region to which the experiment had been intended to be restricted.

From the distribution of the recording-form to 26 observers, it now appears that about 26 records, of from one to 15 days in length per station, will be received. On April 22, 1939, 90 reports had been received from 11 observers. It is believed that these may bring together a number of new constructive criticisms, and possibly support modification in the report-form.

When the results of this first trial are consolidated, it is the purpose of this group to circulate the report-form, a report on its trial-use, and our conclusions therefrom, to all of the members of the Water Resources Committee and to a selected group of other competent advisers, for their constructive comment and that of the Committee on Snow. It is our hope that the procedure may prove worthy of the cooperation and sponsorship of that Committee.

To the copy of this report, which is being filed with the Chairman of the Committee on Snow, there is appended an exhibit consisting of a copy of the report-form with its explanatory supplement and a copy of the memorandum upon which the cooperating agencies based their letters to their observers when they transmitted the form for their use.

Water Resources Committee,
National Resources Committee,
Washington, D. C.

## APPENDIX A-1--COPY OF SUGGESTED MEMORANDUM TO SELECTED OBSERVERS RELATIVE TO SNOW-CLASSIFICATION REPORT-FORM

United States Department of Agriculture,
Weather Bureau

Stimulated by information which was brought together at the Western Interstate Snow-Survey Conference at Davis, California, January 8, 1938, we have given some thought to the practical losses which result from the wide variation in terms used in different localities to classify snow-condition. We have concluded that it is highly desirable to make a practical exploration, by field-trial, of the possibility of finding terms to describe snow-condition which may prove of greatest value to those interested in winter sports and, at the same time, be sufficiently exact and identical in their meaning at all reporting stations to make the reports useful also as scientific basic data for other purposes. We are asking you, as one of a limited number of selected observers, to help us in this preliminary exploratory study.

For a number of reasons it appears desirable to make this trial in the eastern winter-sports areas, where snow-cover conditions are subject to wide local variations and to great variation during the day. Furthermore, the skiing hitherto has been principally on narrow forest-trails which soon become hardpacked, if not icy, and relatively simple reports on the condition of such trails ("good," "fair," "poor," etc.) have sufficed for the great majority of skiers. But the present trend is toward more open-slope skiing and ski-touring. This will require a broadening of the field of reporting; it is our belief that every effort should be made to base the broadened nomenclature upon principles which are scientifically correct and exact enough to enable a skier to become snow-wise and more competent to make his own forecasts from the weather-reports as to what will have happened to the snow by the time he gets there. It is believed that in Europe such study and skill in prediction of snow-conditions is a recognized qualification of an adept in winter sports.

There are doubtless many more transitional forms of snow than are apprehended by even the experienced skiers in the eastern United States, some knowledge of which is essential to their becoming well-rounded adepts in winter sports. A reporting service will ordinarily, in practice, need to use only a very few of them in any one section or time of the season. Therefore, a list of terms which, compared with the present elemental terms like "good" and "poor," may seem a complex multiplicity, need not be a drawback. The classification should at least cover all of the forms which are likely to occur in one region during any winter, if it is to aid practical skiers in becoming competent enough in forecasting changes to add to their skill in forecasting the occurrence of the conditions which their particular degree of skill requires for their full enjoyment of the sport.

We are sending you herewith a small supply of report-forms on which are set up in parallel three classifications of snow-conditions which are currently in use in the United States, together with a fourth classification based on European practice which takes into account the transitions from one form to another. The fifth column provides for recording the judgment of a local ski-expert, selected by you for his competence as an adviser, as to whether snow-conditions are excellent, good, fair, or poor, for each of the ski-areas considered--down-hill practice-slope, down-hill trails, and cross-country touring. The final column provides for a record of certain tests, in parallel with the reports on conditions. On each day reported upon, it is desired that a record be made in all of these columns. There is enclosed herewith a separate explanation of the desired tests.

It is hoped that a careful use of this form may disclose, through the relative consistency of the classifications in comparison with skiing conditions and the physical tests, the terms for which there appears to be a practical need in the area reported upon. One of the enclosed forms is filled out completely as a specimen.

We hope that through your interest and help it may be possible to obtain some preliminary experience which may at least lead to improvements in the form and content of this report-form in advance of its more extended use next winter.

Your use of this report-form on as many days as possible, and in particular your very full comments leading to the improvement of this reporting process, will be cordially appreciated. We are forwarding you also a supply of addressed franked envelopes for use in mailing your reports as each is completed.

Thorndike Saville, Dean, College of Engineering, New York University
Merrill Bernard, Chief, River and Flood Division, United States Weather Bureau
Edd. F. Preece, Senior Engineer, National Park Service
E. B. Ballard, Associate Coordinator, National Park Service

File No. ______

Date ____________19___

Time of Observation ______

### REPORT-FORM OF SNOW-CONDITIONS BY VARIOUS CLASSIFICATIONS IN CURRENT USE

______________ (Agency)

______________ (Name of observer)

______________ (Station designation)

Name of classification in general use in this Area: ______________
(Column number below or other description)

In each column, the type of area to which the classification applies is identified as follows:
A = Down-hill practice-slopes; B = Down-hill trails; C = Cross-country touring

In each column, the check-mark (✓) indicates the observer's classification at the time of observation; the plus-mark (+) indicates his prediction (in the light of the weather-forecast at the time of observation) of the classification 48 hours later.

| Classification I | |
|---|---|
| SOFT-SNOW CONDITIONS | |
| a. Fluffy--Large, light, feathery flakes. Scooped up in the hand, it may be blown off like feathers. Even a tennis-ball would drop out of sight in an accumulation of sufficient depth. | |
| b. Powder--Dry, cold, powdery snow; the perfect snow for sleighing and all winter sports. | |
| c. New--(To be used for Weather Bureau purposes for snow which has fallen within 24 hours before Trail-Report is made, and which cannot be described by some other term. That is, if the snow is new and fluffy, fluffy will be checked; but if the snow is new and of a character for which no term is listed here, new will be checked.) | |
| d. Heavy--Occasionally a powder-snow, long before changing to crust, becomes somewhat packed or heavy, so that while skis sink in it readily, there is nevertheless a toughness to the surface which resists against lateral movement of the ski, causing slight difficulty in turning. | |
| e. Sticky--Snow just beginning to melt. Sticky snow can be used by proper waxing of ski. "Powder-snow begins to stick if the air-temperature rises above the freezing point. Sticky snow adheres in big lumps to the running surface of the skis -- Powder-snow begins to stick when it begins to thaw." [Arnold Lunn, Alpine skiing at all heights and seasons, p. 21] | |
| f. Wet--A soggy state intermediate between sticky and slush reached after powder-snow or wind-crust has been thawing for some time. This is the cotton-batting snow from which boys roll big balls, build forts and snowmen. | |
| g. Glazed--A light, thin, transparent glaze frequently forms on any one of the above described sorts of soft snow. It is the result of superficial melting by hot Sun and subsequent freezing. It does not materially hinder use of ski. | |
| h. Slush--(For Weather Bureau purposes check "Thawing".) | |
| HARD-SNOW CONDITIONS | |
| i. Breakable--A crust is "breakable" when it will not hold the full weight of a man on a single ski. This condition renders steering difficult except by jump-turn and when present should always be reported even though the report also shows several inches of soft snow above the crust. All crusts are first classified as "breakable" or "non-breakable". For practical purposes a person not using skis may test a crust by selecting a board three inches wide and having roughly one inch of length for each two pounds of the person's weight. If the crust breaks when he stands on this board, it is to be reported with the word "breakable". | |
| j. Wind--"Wind"-crust is frequently formed by action of the wind on powder-snow. Usually ripple-marks on the surface reveal the origin of this crust. If breakable, report "breakable wind"; otherwise merely "wind". (For Weather Bureau purposes, do not use the combined term "breakable wind". "Breakable" is sufficient.) | |
| k. Common--"Common" crust is the crust formed by light thaw and refreezing; it should, if not "breakable", be reported simply as "common". | |
| l. Icy--"Icy" crust is the hard, ice-like crust formed by freezing of a watery surface after a heavy thaw. Ski even when sharply edged, gets no grip on this surface, which makes skiing quite impossible. Such crust should be reported merely with the one word "icy". | |
| SPRING CONDITIONS | |
| m. Granular--An old, wet snow, in appearance and consistency much like the wet rock-salt used to pack ice-creams. Granular snow is usually found only in the spring and at high altitudes. "Snow that has been melted and re-frozen night after night soon acquires a crystalline character . . . Granular snow yields excellent skiing." [Lunn] | |

| Classification II | |
|---|---|
| a. Dry<br>A light, fluffy snow of low density, easily moved by wind--may be referred to as "powder". | |
| b. Heavy<br>Wet, high density, will not crumble when shoveled or disturbed. | |
| c. Crusted<br>Conditions where freezing has formed a top crust. | |
| d. Packed<br>Condition of crusting due to wind-driven snow; the report should mention whether the crust is firm or breakable under the weight of the skier. | |
| e. Drifted<br>Snow blown into drifts, irregular with firm surface. | |
| f. Granular<br>A condition usually found in old snow during the spring, sometimes referred to as "corn snow". | |

REPORT-FORM OF SNOW-CONDITIONS BY VARIOUS CLASSIFICATIONS IN CURRENT USE--Continued

| Classification III | Classification IV | | |
|---|---|---|---|
| | General classification | Adjective prefixes | Crusts |
| a. Packed snow<br>This is settled snow which will support the weight of of skiers. Normal-packed snow is snow which will support skiers on skis, allowing them to sink in from one to four inches. Icy-packed snow is snow which will completely support skiers on the surface, presenting a hard unbreakable surface to skis. | NEW SNOW<br>a. New dry fluffy powder<br>b. New dry heavy powder<br>c. New damp powder<br>d. New wet snow<br>e. Thawing new snow<br>f. Slush | a. Ice-crusted, breakable<br>b. Ice-crusted, unbreakable<br>c. Drifted<br>d. Dirty, dusty or littered (surface only)<br>e. Freezing | |
| | SETTLED OR OLD SNOW<br>g. Old dry settled powder<br>h. Old wet snow*<br>i. Old damp powder<br>j. Damp old powder<br>k. Thawing old powder*<br>l. Slushy old wet snow* | a.Fluffy<br>b.Heavy<br>c.Fluffy, becoming heavy<br>d. Dirt, dusty or littered<br>e. Freezing (for types marked * only) | a. Refrozen snow<br>b. Glazed old snow<br>c. Rain-crust<br>d. Wind-crust, thick<br>e. Wind-crust, thin<br>f. Sun-crust, breakable<br>g. Sun-crust, softened<br>h. Marble-crust<br>i. Trap-crust |
| b. Soft snow<br>This is soft, unpacked snow into which skiers will sink more than four inches. Further classification as to consistency should include powder (meaning light, fluffy snow), medium (meaning normal soft snow) and wet (meaning heavy, wet snow). | NEW FIRN SNOW ("SPRING SNOW")<br>m. Hard spring snow ("Frozen corn") ("Frozen granular)<br>n. Soft spring snow ("Wet corn")<br>o. Film crust<br>p. Perforated crust<br>1. Sun-pits<br>2. Sun-cups<br>3. Foam-crust<br>4. Plough-shores<br>5. Nieve penitente | a. Shallow<br>b. Deep<br>c. Dirty or littered | |
| c. Variable snow<br>This is snow which, as implied, may be both soft and packed. Wind often packs snow in spots while other portions of the surface are soft. | ADVANCED FIRN-SNOW, AND NÉVÉ<br>q. Firn snow<br>1. Hard firn (night crust)<br>2. Soft firn (daytime, loose watery grains)<br>3. Dry corn<br>4. Perforated crusts<br>r. Firn ice<br>s. Névé<br>t. Glacier ice | | |
| d. Breakable crust<br>This is snow with a surface-crust which breaks under the weight of the skier. It is treacherous and skiers should be warned in advance of its existence in any area on a particular week-end. | | | |

## REPORT-FORM OF SNOW-CONDITIONS BY VARIOUS CLASSIFICATIONS IN CURRENT USE--Concluded

| Classification V | | Tests | |
|---|---|---|---|
| LOCAL SKI-EXPERT'S RATING OF SKIING CONDITIONS | | A. PHYSICAL PROPERTIES<br>1. Density<br>(Measured by one of the existing types of snow-samplers) | |
| (Excellent, Good, Fair, or Poor) | | 2. Texture<br>(Measured by eye, or, more elaborately, by photographic means) | |
| a. On down-hill practice slopes | | 3. Degree of liquid $H_2O$<br>(Measured by a simple calorimeter method by determining final temperature of a snow-sample dropped in known quantity of boiling water) | |
| b. On down-hill trails | | 4. Temperature<br>(Measured by a thermometer of extremely small heat-capacity (preferably thermocouple method) | |
| c. For cross-country touring | | 5. Adhesion<br>(Measured by the force required (on a spring-balance) to start a standard "ski-section" moving on the snow-surface and the force required to keep it sliding.) | |
| | | 6. Penetrability<br>(Measured on a compression spring-balance, the force required to push a plate of certain area into the snow different distances (see Seligman, p. 7). | |
| | | 7. Breaking point of crust<br>(Measure force required to break crust. This is a finer measurement than "breakable" or "unbreakable".) | |
| | | B. CONDITIONS UNDER WHICH SNOW FELL<br>1. Air-temperature | |
| | | 2. Wind-velocity | |
| | | 3. Character of falling snow<br>(Wet or dry, single depth or clusters) | |
| | | 4. Drifting or in city where it fell | |
| | | 5. Depth of new snowfall | |
| | | C. HISTORY SINCE ACCUMULATION<br>1. Age | |
| | | 2. Meteorological sequence | |
| | | 3. Depth of old snow-cover | |
| | | D. PRESENT WEATHER-CONDITIONS<br>1. Air-temperature | |
| | | 2. Sky-condition | |
| | | 3. Wind-velocity | |

## APPENDIX A-2--SUPPLEMENT TO REPORT OF SNOW-CONDITIONS: DEFINITIONS APPLYING TO CLASSIFICATION IV

### General classification

NEW SNOW

(a) New Dry Fluffy Powder

Falls at relatively low temperatures, usually during light winds or calm. Settles quickly when reworked by wind and drifting, and by its own weight if the depth of fall is great; the fluffiest is therefore in the uppermost few inches. Water content usually very low, always well below the "normal" of one inch of water from ten inches of snow on the ground.

(b) New Dry Heavy Powder

Falls at moderate temperatures below freezing, low enough to keep the grains dry and small. Water content is sometimes high, and its resistance to plowing and turning of skis is then quite noticeable. Cannot be settled as much as fluffy snow, but drifting and reworking by wind will alter its consistency from the usual floury texture to fine sugary texture.

(c) New Damp Powder

This is not thawing snow nor snow with big wet flakes; its dampness, if not evident from appearance, is reflected in its properties. The difference between "new damp powder" and "new dry heavy powder" probably consists largely in difference in snow temperature; the change from new dry to new damp powder may take place suddenly with slight rise of temperature, though no other change is obvious except by crystallographic analysis with a lens. The term "dampness" is thus not a strictly scientific attribute for this snow, but its behavior is like that which is effected by so-called "dampness" in snow that is obviously wetter. These may vary and undergo transitions as follows:

(1) Will pack only a little under considerable pressure, but will stick considerably to a pressing surface (as a ski); hence will clog skis when climbing but not when sliding down.

(2) May pack readily under moderate or only slight pressure, but at the same time stick little or not at all to the pressing surface.

(3) May pack and stick readily under slight or moderate pressure.

The difference between the characteristics (1), (2), and (3) may be only that found for the same snow under different pressures or kinds of skis; or it may be due to different layers in the snow bed, or to a modifying process of the snow from evaporation and recrystallization among the grains.

(d) New Wet Snow

Falls in large wet flakes at temperatures just below freezing, and does not thaw any more after reaching the ground. Packs very easily on slightest pressure, but may not stick to a ski if sufficient gliding pressure is applied. This snow state depends on a limited zone of temperature; it therefore usually undergoes alteration by thawing, or by drying out by colder weather soon after it falls.

(e) Thawing New Snow

This is snow that fell as dry or damp new snow but very soon after falling underwent melting from the top of its surface downward, by warm air above the freezing point or by a hot sun with the temperature only a little below the freezing point. It exhibits transition phases somewhat similar to those of "new damp powder". It is apt to be quite different from "new wet snow", in being wettest at the top and relatively dry at the bottom, whereas "new wet snow" is as a rule wet through; furthermore its crystals were originally different in size and form from those of "new wet snow". While in some cases "thawing new snow" might be considered as "old wet snow" (depending on how soon thawing set in and progressed after the snow fell), "old wet snow" is considered in this classification as a "settled or old snow" type.

(f) Slush

This is watery, soupy new snow, from rain or rapid thaw. (There is presumably no difference between new slush and slush from old snow.)

SETTLED OR OLD SNOW

(g) Old Dry Settled Powder

(1) Fluffy; (2) heavy; (3) fluffy becoming heavy, that is, heavy in certain layers, fluffy in others.

Length of time the snow has lain on the ground may be the only criterion between "old dry settled powder" and "new dry snow". After several days "new dry snow" should be called "old dry settled powder" even though no obvious change has taken place. For scientific purposes the settling which always takes place should be indicated by a test, either mechanical or crystallographic.

SETTLED OR OLD SNOW (Continued)

(h) Wet Snow

This is "new snow" that has been thawed moderately for some time.

(i) Old Damp Powder

This is the same as "new damp powder" except that it usually occurs under a crust or with thawing snow on top, and of course has undergone settling and alteration in its crystals.

(j) Damp Old Powder

This is dry powder that is becoming sticky or is packing from the surface downward due to rising air temperature and/or moist winds, but in which actual thawing has not yet begun. It is an evolution of snow on the ground from "new dry powder" through stages similar to those characteristics of "new damp powder"; "new damp powder" originally fell in that condition, whereas "old damp powder" developed similar characteristics from a condition that was originally dryer. The resulting condition is probably not exactly the same in the two cases, as settling and other processes due to aging are brought into effect in the case of "damp old powder".

(k) Thawing Old Powder

This is wet packing snow that may or may not stick readily; the temperature is above freezing, or is far below if there is hot sun. While practically the same as "old wet snow", the cause of the wetness is here definitely implied, and thawing has been going on for only a short time.

(l) Slushy Old Wet Snow

(No definition necessary)

NEW FIRN-SNOW ("Spring Snow")

(m) Hard Spring Snow ("Frozen corn", "Frozen granular")

This is generally a "night crust" due to temperature falling below freezing during the night.

(n) Soft Spring Snow ("Wet corn")

This is a daytime thawing-phase; the grains are moderately lubricated with melt-water. (The essential difference between "spring snow" and "telemark snow" or "softened sun-crust", is that the latter is finer grained and individual grains are therefore not easily distinguishable on account of finer grain. There is, therefore, probably relatively more water present in telemark snow than in spring snow; the difference between the two types is not very marked.)

(o) Film Crust

This is a special case of the "hard spring snow"; it may evolve from "old wind crusts" or from "marble-crust".

(p) Perforated Crusts

(1) Sun-pits

(2) Sun-cups

These are differences in degree of the process which follows the tendency of the Sun when striking a crusted snow slope to act more powerfully upon the tiny depressions into which its rays are concentrated so that they become evaporated on the side opposite the Sun's noonday position. After several days of hot still conditions, inequalities in the original surface are intensified until quite deep pits have formed.

(3) Foam-crust

Small overlapping waves of crust like sea-foam resulting from combined action of wind and Sun.

(4) Plough-shares

These are an excessive development of "foam-crust" due to intensified evaporation similar to that which forms "sun-pits" and "sun-cups"; the individual plough-share faces the Sun at its hottest point.

(5) Nieve penitente

The "penitent snow" of the Andes is snow or ice which has been ablated by Sun and wind until curious pillars or columns or snow remain standing out from the disappearing snow-level.

ADVANCED FIRN-SNOW AND NÉVÉ

(q) Firn-snow

(1) Hard firn (night-crust)

(2) Soft firn (daytime)

(Grains very loose with melt-water)

(3) Dry corn

Well-drained subsurface layers of loose dry grains. This is a surface condition only when uncovered by an avalanche.

ADVANCED FIRN-SNOW AND NÉVÉ (Continued)

(4) Perforated crusts

These are the same as listed under (p) but more advanced.

(r) Firn-ice

This is firn-snow which is becoming compacted into névé or glacier-ice.

(s) Névé

This is partially compacted granular snow such as is typical of the surface-part of the upper end of a glacier.

(t) Glacier-ice

This is the complete conversion of old snow under aging and pressure into ice.

## Adjective prefixes

FOR NEW-SNOW TYPES

(a) Ice-crusted, breakable

(b) Ice-crusted, unbreakable

These descriptions are to be used only when a glaze or sleet or rain freezes immediately on top of the fall of snow. Ordinarily the full development of thaw crusts comes with the passage of a longer time after the fresh fall; crusts in general are under the "settled or old snow" types.

(c) Drifted (or drifting)

(No definition needed)

(d) Dirty, Dusty or Littered

(These refer to the surface-condition only.)

(e) Freezing

This is used to indicate the tendency at the time of reporting, when freezing has not been definitely consummated and its effects are not completely evident.

## Crusts

These are to be used to modify any of the "settled or old snow" types; the terms may be used as additional descriptive words or as independent descriptions of the surface as the purposes warrant.

(a) Refrozen Snow

This may be wet or thawing with rough surface, breakable or unbreakable. This may come as the result of a cold wave after a thaw, or only during night hours when the temperature fell slightly below freezing.

(b) Glazed Old Snow

This may be (1) a smooth "glare-ice", due to freezing rain or fog, or (2) a pebbly semi-clear ice-coating due to the freezing of sleet or of sleet and rain. It may be breakable or unbreakable, but is always hard and brittle.

(c) Rain-crust

This may be formed on old or new snow. This crust is normally fairly thick, but the snow-grains are cemented without loss of the surface-appearance of a snowy texture; normally there is no glazed surface, and the pock-marks from rain and the drifting of water from trees may be characteristic. It may be breakable or unbreakable.

(d) Wind-crust

On old or new snow, breakable or unbreakable; thick--this wind slab breaks like a pie-crust if loose powder is beneath it.

(e) Wind-crust, thin

A ski will cut through this crust rather than break it.

(f) Sun-crust, breakable

(Probably sun-crust is never unbreakable.)

(g) Sun-crust, softened

(Telemark-snow--this is soft, wet, often firn-snow-like, granular material, melted by the Sun from a former sun-crust. It may be crust by night and softened by day, alternately. Though material with similar characteristics may occasionally form from crusts other than sun-crust, normally the thaw of other crusts produces old wet snow or slush. The softened sun-crust is actually the beginning stage of "spring snow" or "wet corn"; hence by a strict construction it hardly belongs under the "settled snow" category.

(h) Marble-crust

This is a thick wind-crust (wind-slab) which has been rain-soaked or partly thawed or wind-moistened, and subsequently refrozen hard.

(i) Trap-crust

This is any kind of crust which is variable in supporting power--breakable in spots and unbreakable in others. The term should be used as an additional adjective to the other crusts to indicate skiing conditions.

### Notes on tests
(Extreme right-hand column of Report-Form)

It is expected that standardized procedures for the tests listed will be developed later. The proposed tests are set out on this trial-form at this time principally to acquaint the selected cooperating observers with the intended correlation between snow-type classifications and their characteristics as shown by tests; and reports on physical properties (A-1 to A-7) are not asked at this time. It is desired, however, to have the observer's reports of "Condition under which snow fell," "History since accumulation," and "Present weather-conditions." His comments and practical suggestions are particularly desired.

U. S. Weather Bureau,
Washington, D. C.

## APPENDIX B--NOTES ON WINTER-SPORT FORECASTING

Salvatore Pagliuca

The rapid growth of winter sports, and particularly skiing, in New England, in the past few years, and the ever-increasing demand on the meteorologist to forecast conditions likely to be expected at a certain time over a certain terrain, have created a definite problem.

R. G. Stone of the Blue Hill Observatory has carried on some interesting statistical and observational surveys of the snow-cover in New England at the request of the Recreational Planning Branch of the National Park Service in an effort to establish the relative merits of the various areas for winter sports purposes [Trans. Amer. Geophys. Union, 1938, part II, pp. 720-724].

His attempt at a classification of the snow-types, inspired by the great work of Seligman, and the inadequacy of the methods used in this country, is a further effort at a coordination of the existing knowledge on snow [Bull. Amer. Met. Soc., v. 18, pp. 5-10 and pp. 47-53 (1937), v. 19, pp. 80-83 (1938)].

Such a knowledge, with due allowance to the limitations of statistical methods, should also prove useful to private business depending on winter-sport activities.

Actual experience has shown that the average skier, representing by far the largest percentage of the users of our snow-fields, is interested in the day-to-day information on snow-conditions and primarily whether or not there will be sufficient snow to ski on by the time he reaches a certain skiing-ground. Once he is assured that he will find sufficient snow the next question is, what type of snow-surface will he find over various portions of certain trails and slopes? Finally, how the weather is going to be while skiing. The problem which I have stated in plain words has proved to be one of first magnitude and requiring that the forecaster be well acquainted with mountain meteorology, be familiar with the territory for which he is forecasting, and have a definite understanding of the ever-changing requirements of winter sports and winter sportsmen. It is immediately apparent that a winter-sport forecast should cover altitude in preference to lowland. A first attack on the problem has been made for the past two winters in New England by the Yankee Network Weather Service which I have the privilege of directing.

Our first move was to contact reliable observers, a task not at all simple considering that most observers are engaged in some sort of business more or less directly affected by winter-sport activities.

Then we established radio contacts by means of ultra-short waves with the Mount Washington Observatory which in turn contacted, also on short waves, the Mount Whiteface Observatory in the Adirondacks and several radio amateurs in the White Mountain regions. This radio circuit was extremely effective in conveying to our office in Boston several times a day reliable and up-to-the-minute reports on snow- and weather-conditions. For simplicity no attempt was made to introduce any new terminology and the standard terms used by the "Ski Bulletin" and already familiar to New England skiers were used.

At this point I wish to emphasize that skiing is a sport and not a science. Desirable as it is to have a complete nomenclature based on physical and crystallographic principles, it is, in my opinion, better to use simple descriptive words in preference to unusual, foreign or Latin words.

A special map showing the principal skiing-centers was made and for each center the daily value of the snow-depth, the surface-type, and the temperature was entered. This enabled the forecaster to visualize the recent history of each section and be in a better position to anticipate the effects of future weather on the snow-cover and on the type of surface. For this purpose the weather-observations from the top of Mount Washington, Mount Whiteface, and lately from Mount Mansfield (Vermont), proved to be an excellent supplement to the surface-map and upper-air information. The forecasts were not issued in a stereotyped form, but rather they consisted of a brief discussion of the past history of the snow-cover, a description of its most recent changes (during the day for the evening's forecast, and during the night for the morning's forecasts). Finally a discussion of how the future weather was going to affect conditions at all levels.

This involved:

(1) A forecast of temperature-range at three different altitudes which, for convenience, were named: low altitude, up to 2000 feet; moderate altitude, 2000 to 4000 feet; high altitude, 4000 to 6000 feet.

(2) A forecast of the amount and type of precipitation at the various elevations stating definitely how many inches of new snow were expected and what type (wet, granular, dry powder, fluffy).

(3) A forecast of direction and velocity of the wind indicating the degree of drifting likely to be expected with the snowfall and after snow had ended.

General remarks, frequently originating from observers in the field, were added. For instance, if a section of the trail had had the surface-crust broken out offering fine skiing on the old snow it was so stated, thus saving the day for skiers who otherwise would have kept away from a region reported simply as having unbreakable crust.

In forecasting the general weather for the region, skiers were often warned of severe combinations of extremes of weather at the higher levels.

Although the practice of stating whether skiing is poor, fair, good, or excellent is generally condemned, we found it worth while, in the interests of the large number of inexperienced sportsmen, to add such remarks, since good skiers generally use their own judgment based on snow-reports and on the weather-discussion of the forecaster.

Finally the actual reports as received from the field-men, together with their comments and a report of the condition of the roads leading to the winter-sports centers. All this information was broadcast twice a day, seven days a week over the Yankee Network including 16 stations scattered all over New England. In addition there was a daily broadcast at 5:15 p.m. over station WAAB and a special Friday evening broadcast at 7:15 p.m. over WNAC in Boston. The Yankee Network winter-sports broadcast forms a part of a 15-minute program prepared by the Yankee Network Weather Service, dedicated entirely to weather-forecasting and reporting for general and special purposes. Winter-sports broadcasts begin with the first skiable snowfall and are kept continuously so long as there is snow in Tuckerman's Ravine which means June or even early July. This year the winter snowfalls were nearly normal, but a series of March and mid-April snowfalls increased the snow-cover over northern New England to its highest levels of the season. A few comparisons between snow-depths in the middle of April this year and last year indicate that at Pinkham Notch and on Mount Cardigan in New Hampshire the snow-cover was three times greater this year than last year. On Mount Mansfield the snow-cover at the summit was twice as deep this year as last year and the base nearly four times deeper than last year. At the summit of Mount Washington there was practically no snow on ground in mid-April last year and there was 35 inches this year.

One important aspect of our service was to advise racing committees on snow- and weather-conditions expected to prevail during skiing contests, in order to assure successful and safe performance.

The most interesting case this year was forecasting for the classic New England skiing-competition known as the American Inferno. The course ran from the summit of Mount Washington (elevation, 6288 feet) over the headwall of Tuckerman's Ravine to the eastern base in Pinkham Notch (elevation, 2040 feet). The distance, 3-1/8 miles with a total drop of slightly more than 4200 feet. At its uppermost portion, the headwall ranges in steepness from 60° to nearly vertical. Anyone familiar with the Mount Washington weather will readily realize the difficulties of forecasting very much in advance snow-conditions, visibility, and weather for that region. Twice it was found advisable to postpone the race because of poor visibility and generally adverse weather-conditions. On the morning of April 15 a moderate but quite active disturbance was centered over eastern Maine, causing rain and snow over an extensive area. The ski-race was postponed a second time, but a fresh invasion of cold and dry polar-continental air gave assurance that the following day would be ideal for racing.

On the evening of April 15 the following forecast was broadcast by the Yankee Network Weather Service: "Weather-conditions tomorrow will be very favorable for skiing in northern New England. The strong winds and cloudiness which still prevail at the higher altitudes will improve considerably by tomorrow. The ski-race from the top of Mount Washington to Pinkham Notch over the headwall of Tuckerman's Ravine, known as the American Inferno, will be run tomorrow at about noon. The following conditions are expected to prevail over the course: Cloudless sky, with the summit of Mount Washington out of clouds, temperatures well below freezing from the summit to the Hermit Lake Shelter, wherefrom it will gradually moderate to become near or slightly above freezing over the lower portion of the Sherbourne Trail into Pinkham Notch. The direct effect of sunshine will result in sufficient softening of the surface for adequate control but on the whole the course will be very fast. While the upper cone will be found hard-packed and quite rough, the headwall will be in excellent condition with slightly packed dry powder. Strong northwest winds will prevail on the summit rapidly diminishing to fresh and moderate on the headwall ..."

The race was held on schedule with a correct verification of the forecast. It was later realized that had the race not been held on that day there would have been no more chances of running it, as the snow began to disappear rapidly at the summit and at the lower portion of the trails. The results of the race are an all-time record for speed and safety. The winner finished in 6 minutes 29-2/5 seconds. Of the 44 competitors who started, 42 finished. One did not finish because he broke his skis and another because of a minor injury to his ankle.

It is our aim to extend the short-wave radio network to include as many skiing centers as possible so as to make available to our Boston office several times a day up-to-the-minute reports from the field.

And to make the whole thing still more interesting we may have each observer broadcast his observations directly to the audience and have the forecaster from our Boston studio add his forecast for the particular winter-sport center.

Yankee Network Weather Service,
Boston, Massachusetts

## REPORT OF COMMITTEE ON EVAPORATION FROM WATER-SURFACES, MARCH 1939

S. T. Harding, Chairman

The membership of the Committee was increased in 1938 by the addition of E. W. Lane. The present membership is as follows: Harry F. Blaney, N. W. Cummings, Robert Follansbee, J. A. Folse, S. T. Harding, Robert E. Horton, Ivan E. Houk, E. W. Lane, R. E. Kennedy, G. F. McEwen, Carl Rohwer, C. M. Saville, Thorndike Saville.

The Committee's recommendations for a program of investigations in evaporation from water-surfaces were the basis of the Committee's report in April 1938. This report recommended that such work should be undertaken adjacent to some large water-area for which the evaporation could be measured. No means of financing such a program has been found. In July 1938 a Class A Weather Bureau pan and a screened pan were installed adjacent to Lake Elsinore in Southern California. This represents a start toward the type of study recommended.

The members of the Committee have assisted the Chairman in the preparation of the Report on Evaporation for the United States for the International Assembly on Hydrology to be held in Washington during September, 1939. They have also assisted in the assembling of references on evaporation for the 1938 bibliography on hydrology.

12 Engineering Building,
Berkeley, California

# REPORT OF COMMITTEE ON GLACIERS, APRIL 1939

François E. Matthes, Chairman

The Committee on Glaciers at present is constituted as follows:

Harry Fielding Reid--Professor-Emeritus of Geology, Johns Hopkins University (former member of the International Glacier Commission), 608 Cathedral Street, Baltimore, Maryland

William H. Hobbs--Professor-Emeritus of Geology, University of Michigan (until recently Vice-President of the International Glacier Commission, at present associate member), Ann Arbor, Michigan

J. E. Church--Professor of Classics, University of Nevada (President of the International Commission of Snow, and Chairman of the Committee on Snow of the Section of Hydrology, American Geophysical Union), Reno, Nevada

Colonel Lawrence Martin--Chief of the Division of Maps, Library of Congress, Washington, D. C.

Wm. Osgood Field, Jr.--Explorer, 18 West Twelfth Street, New York, N. Y.

Earl A. Trager--Chief of the Naturalist Division, National Park Service, Washington, D. C.

Glenn L. Parker--District Engineer, Water Resources Branch, United States Geological Survey, 406 Federal Building, Tacoma, Washington

Oliver Kehrlein--Chairman, Committee on Glacier Studies, Sierra Club, 1050 Mills Tower, San Francisco, California

Kenneth N. Phillips--Associate Hydraulic Engineer, Water Resources Branch, United States Geological Survey, Chairman, Research Committee of the Mazamas, 606 Post-Office Building, Portland, Oregon

William S. Cooper--Professor of Botany, University of Minnesota, Minneapolis, Minnesota

Gerald FitzGerald, Senior Topographic Engineer, Alaska Branch, United States Geological Survey, Washington, D. C.

Laurence M. Gould, Professor of Geology, Carleton College, Northfield, Minnesota

François E. Matthes, Chairman, Senior Geologist, Section of Glacial Geology, United States Geological Survey (titular member of the International Glacier Commission), Washington, D. C.

In 1938, as in previous years, the Committee devoted its energies primarily to the collecting of data on the variations in length and volume of American glaciers, it being felt that the maintenance of a continuous record of these variations is of prime importance, not only to hydrology and glaciology, but, as has become increasingly evident recently, also to climatology, geomorphology, geography, ecology, history, and archaeology. As the time available for the work of the Committee is limited and does not permit covering the entire field of glaciology, it seems best to devote it before all else to this line of research which yields results of value to so many different sciences. Besides, the gathering of data on glacier-oscillations is not a one-man job that can be taken up or dropped at convenience from time to time, but is an organized and far-flung enterprise whose success depends upon the faithful cooperation of many volunteer workers located in different parts of the country. Such an enterprise, once launched, must be kept running or it will disintegrate and the precious enthusiasm of the field-workers will be lost.

The systematic measuring of glacier-oscillations from year to year has now been carried on in this country since 1931 (in one locality since 1918); in Europe it was inaugurated in 1894 and has been carried on continuously ever since, except for the unfortunate intermission that was caused by the World War. The value of the records obtained is not to be gaged by the variations indicated in any one year, or group of years, for such passing variations reflect merely the effects of short-time fluctuations in precipitation and temperature, and of various local factors as well. Taken collectively, however, in relation to long-time swings in climatic conditions comprising decades, centuries, and even thousands of years, they are found to possess great significance. That fact has long been recognized and, as a consequence, more than one glaciologist has been spurred on to search for data that would permit extension of the plotted curves back into historic times and even farther back into the past.

Successful searches made in the archives of the town of Chamonix, at the foot of the Mont Blanc Chain [Charles Rabot, Récents travaux glaciaires dans les Alpes françaises, La Géographie, v. 30, pp. 257-268, 1915], notably have served to extend the record for the glaciers of the French Alps back to 1580 and for the first time have made it clear that the general recession of those glaciers, which has been in progress during the last few decades, set in shortly after the middle of the nineteenth century. Previous to this there had been an epoch of relatively great glacier-extension that lasted, with minor fluctuations, about 250 years. The glaciers of the French Alps, therefore, are now merely receding back to the positions which they occupied toward the end of the sixteenth century.

More recently Thorarinsson, by searching old records in Iceland, has succeeded in tracing the history of glacier-oscillations on that island back to the year 875, when the Norsemen established their first colonies. This history, significantly, reveals that the present recession of the Iceland glaciers also began shortly after the middle of the nineteenth century [Sigurdur Thorarinsson, Grössenschwankungen der Gletscher in Island, Trans. Internat. Commissions of Snow and of Glaciers, Washington, 1939].

Doubtless it is no mere coincidence that recent observations by Munday [W. A. Don Munday, The last advance of the glaciers in the Coast Mountains of British Columbia, Trans. Internat. Commissions of Snow and of Glaciers, Washington, 1939] on the great Klinaklini and Franklin glaciers, in British Columbia, show that these glaciers also are receding from a maximum advance that must have occurred shortly after the middle of the nineteenth century. And the record of the Nisqually Glacier, on Mount Rainier, which reaches back to 1857, is of a closely similar nature.

Thus, it will be seen, considerable headway has recently been made in extending the curve of glacier-oscillations back into historic times. Moreover, the results from widely different parts of the world turn out to be gratifyingly accordant and already give us a perspective of the last long-time swing of which the year-to-year details are being measured at the present time. However, during the past year some progress has been made also in extending the curve of glacier-oscillations, or at least in determining its general character, for several thousand years back into the postglacial interval, thereby making clear the relations which the glacier-oscillations of modern times bear to those of the Pleistocene ice-age. And that progress is based on American data. A full account of it would far exceed the proper limits for a report of this kind and will be presented elsewhere, but a brief outline is appropriate here, as it is distinctly a product of research done by this Committee.

It is commonly assumed that the glaciers now existing on the higher mountains of the Earth are dwindling remnants of the once far more extensive ice-masses of the Pleistocene ice-age. For the ice-caps of Antarctica, Greenland, and Iceland, for the great trunk-glaciers of Alaska and British Columbia, and even for the major ice-streams on such peaks as Mount Rainier, Mount Baker, and Mount Olympus--to limit the discussion to the North American Continent--the assumption probably is valid, but that it can not be extended to all of the numerous cirque glaciers that exist at present on the Cascade Range, the Sierra Nevada, and the principal ranges of the Rocky Mountain System within the United States, is now rather definitely indicated by recent studies by the Chairman of this Committee in the Sierra Nevada and the adjacent Owens Valley. These studies, in his opinion, leave little doubt that the fifty-odd cirque glaciers of the Sierra Nevada and, by implication, the hundreds of similar small glaciers on the other ranges mentioned, are not relics of the ice-age but represent a new generation of ice-bodies that came into being less than 4000 years ago--that is, fully 6000 years after the Pleistocene ice-age came to an end.

The proof is found in the Post-Pleistocene history of Owens Lake, as recently reinterpreted by Antevs [Ernst Antevs, Post-pluvial climatic variations in the Southwest, Bull. Amer. Met. Soc., v. 19, pp. 190-193, 1938]. From the amount of salt which Owens Lake contained in 1912, prior to the diversion of water from Owens River into the Los Angeles Aqueduct, and from the known quantities of salt which the River then brought into the Lake, on an average, annually, Gale had previously calculated that the concentration required, in round numbers, 4000 years [Hoyt S. Gale, Salines in the Owens, Searles, and Panamint basins, southern California, U. S. Geol. Surv. Bull. 580, pp. 251-323, 1915]. He assumed that the concentration began when the Lake ceased to overflow, but Antevs rightly points out that there could have been no overflow 4000 years ago, as that was the end of a long period of warmer and drier climatic conditions than prevail at the present time. The greatest recorded depth of the Lake, in 1872, following a series of wet years attested by tree-rings, was only 50 feet. To overflow the Lake would have had to rise 163 feet higher and spread over more than double the area. There would have been required, under the climatic conditions of the middle Post-Pleistocene, three times the inflow that occurred during the wet years mentioned, and that, as Antevs puts it, is "practically out of the question."

His reinterpretation is that the large and deep Owens Lake of Pleistocene times, which did overflow during the height of glacial conditions, dried up completely during the warm, dry middle third of the Post-Pleistocene interval, and that the modern, relatively small and shallow Owens Lake came into existence 4000 years ago, with the advent of the cooler and moister conditions which have persisted, with various fluctuations, until the present time. The climatic changes during the Post-Pleistocene interval postulated by Antevs, it should be said, are now well established by several different lines of evidence, and his interpretation is supported by what is known of the Post-Pleistocene history of Lake Lahontan and other lakes in the Great Basin.

Antevs further holds that after the ancient Owens Lake had dried up the remaining salt-crust became buried under alluvial materials and wind-blown sand. Its desiccated basin thus was "freshened" in the same manner that was suggested by Van Winkle for the basins of Abert Lake and Summer

Lake, in southern Oregon [W. Van Winkle, Quality of the surface waters of Oregon, U. S. Geol. Surv. W.-S., p. 364, 1914; see also pp. 117-123], and as a consequence salt-concentration must have begun anew in the modern Owens Lake. Its salt-content in 1912, on which Gale based his computations, therefore was a fairly reliable index of its age.

Now it is to be borne in mind that Owens Lake is fed very largely by the melt-water that flows from the snow-fields and glaciers of the Sierra Nevada. During the warm, dry middle third of the Post-Pleistocene interval, doubtless, rainfall in the Great Basin was even scantier than it is at present, therefore it is reasonably certain that the drying up of the ancient lake was caused by a deficiency of snow on the Sierra Nevada, coupled with higher summer temperatures. However, from the measurements and observations on the glaciers of Yosemite National Park which have been carried on for a number of years by the Park Naturalist and his staff, at the request of the Committee on Glaciers, it is evident that those small ice-bodies are very delicately adjusted to the average climatic conditions of the present time. Their life "hangs by a thread," so to speak. Even a single winter of scanty snowfall, followed by an unusually warm summer, reduces them at an alarming rate; and it is obvious to any one acquainted with their fluctuations from year to year, that a sustained decrease in snowfall, accompanied by slightly higher temperatures, would destroy them all in less than a century. There is, then, every reason to believe, that when the ancient Owens Lake dried up the Sierra Nevada was stripped of all its ice, and conversely, that when the new shallow lake came into existence new small glaciers were being formed on the range--the same glaciers which, with sundry fluctuations in volume have persisted until the present day. Those glaciers therefore are in all probability somewhat less than 4000 years old, and that inference is supported in a general way by the number of annual increment-layers which they contain, though the record presented by those layers is in the nature of things, far from complete.

What has happened in the Sierra Nevada doubtless has happened also on the other mountain ranges in the western United States, for many of the small cirque glaciers on those ranges are fronted, like those of the Sierra Nevada, by very fresh-looking terminal moraines arranged in compact concentric series or combined into one or two massive compound embankments. So recently formed are some of those moraines that their steep sides are still in unstable equilibrium, and the loose blocks and slabs on them slide and roll at the merest touch. The contrast they offer to the nearest moraines that are unquestionably of Pleistocene age already has suggested to more than one observer that they are perhaps products of recently formed, "modern" glaciers rather than youngest recessional moraines of gradually dwindling ice-age glaciers. In regard to this the moraines themselves afford no conclusive proof, but such proof happily has now been found in the rebirth of Owens Lake.

The data that are now at hand concerning the occurrence of modern moraines on our western mountains are still too incomplete to permit definite discrimination between glaciers of recent origin and glaciers left over from the Pleistocene epoch. Nevertheless, enough is known to warrant the general statement that in all probability all of the present glaciers on the Sierra Nevada, all those on the ranges of the Rocky Mountain System within the United States--with the possible exception of a few of the largest in Glacier National Park--all of the lesser glaciers on the Cascade Range and on the Olympic Mountains, belong to the "modern" category, and are not relics of the Pleistocene ice-age at all. And probably only the main ice-tongues on Mount Rainier, Mount Baker, and Mount Olympus have persisted since Pleistocene time, the same as the still larger glaciers in British Columbia and Alaska.

All of the glaciers of the latter class, however, it is manifest from the relatively large scale of their oscillations during the last 100 years, now have far greater extent and volume than they had during the middle third of the Post-Pleistocene interval, and accordingly it may well be said that we are living in an epoch of renewed but moderate glaciation--a "little ice-age," that already has lasted about 4000 years.

The vicissitudes of the glaciers during those 4000 years are recorded, rather obscurely, in their multiple "modern" moraines. The spelling out of that record is still to be done. It is preeminently a task for glacial geologists and will not be enlarged upon here; but as it will serve to link this new chapter of glacier-history right up with the present time, it is nevertheless a matter of some importance to hydrology, climatology, ecology, archaeology, and all the other sciences that reach back into the recent past. Indeed, there already is considerable evidence indicating that the glacier-oscillations of the last few centuries have been among the greatest that have occurred during the 4000-year period, and facts such as these can not be ignored. It is to be hoped, therefore, that this line of research will soon find men willing to engage in it. In Europe a beginning already has been made, but thus far, apparently, without a clear realization that the glacier-oscillations of historic times form part of an essentially new chapter of glacier-history that is separated by a long stretch of time from the "stadial" oscillations that marked the decline of the Pleistocene glaciers.

## OBSERVATIONS ON GLACIERS IN THE CONTINENTAL UNITED STATES AND ALASKA, 1937-1938

Because of the length of the preceding section of this Report, the data under this head will be presented in more condensed form than usually.

Glaciers of the Cascade Mountains--Through the courtesy of E. H. Collins, of the Washington Water Power Company, Spokane, Washington, the Committee this year is able to publish the recession record of the Lyman Glacier, which is situated on a high spur of the Cascade Mountains, to the southeast of Lake Chelan. The record is as follows:

| Year | Recession in feet |
|---|---|
| September 1929 to September 1930 | 65 |
| September 1930 to September 1931 | 79 |
| September 1931 to September 1936 | 289 (average, 57.8 feet per year) |
| September 1936 to September 1937 | 55 |
| September 1937 to September 1938 | 45 |

Average annual recession for the entire period of 9 years = 59.3 feet.

From C. Frank Brockman, Park Naturalist of Mount Rainier National Park, Washington, the following data were received on the recession of the glaciers on Mount Rainier:

| Glacier | Recession in feet | |
|---|---|---|
| | 1936-1937 | 1937-1938 |
| Nisqually | 55 | 90 |
| South Tahoma, | | |
| Point B | 13 | 76 |
| Point C | -- | 78 |
| Carbon | 20 | 18 |
| Emmons | 10 | 107 |
| Paradise, | | |
| Point A | ←— 83 —→ | |
| Point B | 28 | 15 |
| Point C | ←— 60 —→ | |
| Stevens | 187 | 345 |

In addition, a complete resumé of all recession-measurements on the glaciers of Mount Rainier since the time of their inception in 1918 was published by Mr. Brockman [J. Geol., v. 46, pp. 764-781, 1938; also Mount Rainier National Park Nature Notes, v. 15, 1937].

Kenneth N. Phillips, Associate Hydraulic Engineer, United States Geological Survey, and Chairman of the Research Committee of the Mazamas, the mountaineering club of Portland, Oregon, submits the following data on the glaciers of Mount Hood and other peaks in the Cascade Mountains of Oregon:

| Glacier | Recession in feet | |
|---|---|---|
| | 1936-1937 | 1937-1938 |
| Eliot | 21 | 22 |
| Coe | 29 | 20 (11 months) |

In addition, a comparison of the present state of the glaciers with that indicated by photographs taken in 1901 by Dr. Harry Fielding Reid, reveals that Eliot Glacier, from July 23, 1901, to September 18, 1938, had receded a total of 426 feet; White River Glacier (on the south side of Mount Hood), from June 2, 1901, to August 9, 1936, had receded a total distance estimated at 1840 feet; and Newton Clark Glacier, from 1901 to 1937, had receded about 500 feet and had been reduced about 100 feet in thickness.

The total recession of Coe Glacier, from August 26, 1928, when measurements were begun, to August 14, 1938, amounts to 120 feet. On the other hand, the relatively small Ladd Glacier, from August 28, 1927, to August 2, 1936, had receded only ten feet and, in general, showed but little change in appearance.

In a well-illustrated article entitled "Our vanishing glaciers" [Mazama Annual for 1938, pp. 24-41], Mr. Phillips reviews the present state of knowledge concerning the aforementioned glaciers as well as the smaller ice-bodies on Mount Hood known as Glisan Glacier and Langille Glacier; also of the Waldo, Timberline, and Milk Creek glaciers on Mount Jefferson, the Jack Glacier on Three-fingered Jack, the Bend, Crook, and Crater glaciers on Broken Top Mountain, the Dutchman Glacier on Bachelor Butte, and the Diamond Glacier on Diamond Peak. All of these small glaciers are in a state of recession, some of them on the verge of extinction.

Glaciers of the Sierra Nevada, California--As a result of unusually heavy snowfall during the winter of 1937-1938, all of the glaciers on Mount Lyell, Mount Maclure, Mount Dana, and Mount Conness, which are annually measured by Park Naturalist C. A. Harwell, of Yosemite National Park, remained covered with fresh snow throughout the summer and autumn of 1938. No measurements, therefore, could be made.

A visit to the North Palisade Glacier, in the southern part of the Sierra Nevada, by Oliver Kehrlein, Chairman of the Committee on Glacier Studies of the Sierra Club, and François E. Matthes, revealed that that Glacier in the last week of September 1938, still bore at its terminus from three to four feet of fresh snow. In a gully cut in the surface of the Glacier by a stream of melt-water, moreover, there was visible, under the snow, a layer of white névé nine inches thick, left from the preceding year. The surface of the terminus, nevertheless, still lay more than 30 feet below the crest of the moraine-wall, whereas in 1933 it lay only six feet below the crest, and in 1922 it rose above the central sag in the moraine, so that a shallow ice-tongue projected through it for a distance of about 100 yards.

Glaciers of the Rocky Mountains--From Park Naturalist George C. Ruhle the following data were received on the state of the principal glaciers of Glacier National Park, Montana:

Agassiz Glacier, which in 1936 had receded not less than 465 feet since the year before, in the autumn of 1938 was found to have receded only 36 feet in two years. Its upper portion now is almost severed into two parts.

No recession-measurements were made on the Sperry Glacier, but during the month of August a detailed topographic map was made of it on the scale of 1:2400 and with contour-intervals of 20 feet. A similar detailed map had been made of the Grinnell Glacier in 1937; that Glacier on October 6, 1938, showed a recession of 76 feet since the autumn of 1937.

The recessional history of the Grinnell Glacier since 1897 is discussed at some length by George R. Gibson and James L. Dyson in a recent paper on "Grinnell Glacier, Glacier National Park, Montana [Bull. Geol. Soc. Amer., v. 50, pp. 681-696, 1939]. In that paper it is stated that the total recession for the four-year period 1934 to 1937 amounts to 165 feet. Also, that comparison of the level of the northern terminus with reference to the top of the morainal embankment in 1937 with that shown in a photograph taken in 1911 by Dr. Wm. C. Alden, of the United States Geological Survey, indicates that the surface of the Glacier there was lowered fully 80 feet during that 26-year period.

It is further pointed out that the front and sides of the Grinnell Glacier are encircled by a prominent, sharp-crested moraine from which the Glacier appears to have withdrawn within a relatively short period. It stands in places nearly 200 feet above the surface of the ice. All the other glaciers in the Park are similarly fronted by high moraines. That these moraines represent a comparatively long stand by the ice-fronts, the authors infer from their large size. "In addition, as observed adjacent to the east lobe of Blackfoot Glacier, the stand was of sufficient duration to enable streams marginal to the ice to entrench themselves in bed-rock transversely to the slope." In the light of what has been stated in the first section of this Report on the significance of the fresh-looking moraines that front the cirque glaciers in the Sierra Nevada, it can hardly be doubted that these high, sharp-crested moraines adjacent to the glaciers of Glacier National Park also are "modern"--that is, of late Post-Pleistocene age. And it seems highly probable that the Grinnell Glacier and all the other lesser ice-bodies in the Park belong to the new generation that came into existence about 4000 years ago.

From H. R. Gregg, Park Naturalist of Rocky Mountain National Park, Colorado, an elaborate report was received on the Tyndall and Andrews glaciers. Both glaciers were found largely covered with snow from the previous winter, and as this snow-blanket extended out beyond their termini no reliable measurements of advance or recession could be made. The "apparent advance" of Tyndall Glacier since 1937 was reported as 134 feet; that of Andrews Glacier as nearly 65 feet.

Glaciers of Alaska--No measurements were made, during the past year, to the fronts of any of the great Alaskan glaciers, but significant contributions were made to geographic knowledge of the main glacier-bearing mountain districts of Alaska, which are extremely difficult of access and as yet only partly mapped.

Among those contributions is the report by Fred H. Moffit, on the "Geology of the Chitina Valley and adjacent areas" [U. S. Geol. Surv. Bull. 894, 1938]. The glaciers are treated very briefly in the text, but the accompanying "Topographic reconnaissance map of the Chitina Valley and adjacent areas," published on the scale of 1:250,000, offers a wealth of information to the glaciologist. It covers a large part of the broadly ice-mantled Wrangell Mountains, from Mount Wrangell, on the northwest, to Mount Bona and Mount Bear, on the southeast, as well as a considerable portion of the Chugach Mountains, to the west and the east of the Copper River Valley. The map is compiled from several different sources of data, including surveys by the International Boundary Commission, the Copper River and Northwestern Railway, and the United States Geological Survey. It is a work of many years, some of the surveys dating back to 1900.

Another outstanding contribution is that by Bradford Washburn, who on a series of well-planned air-plane flights in 1937 and 1938, took hundreds of excellent oblique aerial photographs showing the geographic features of the most extensively ice-covered mountain areas of southeastern Alaska and adjoining portions of Canada. These areas, aggregating several thousand square miles in extent, include the great St. Elias Range, the Wrangell Mountains, the Chugach Mountains, and parts of the Alaska Range, in Mount McKinley National Park. In addition, vertical photographs were taken showing the positions of the glacier-fronts in Prince William Sound and in the vicinity of Yakutat Bay. So completely do these remarkably clear photographs cover the areas flown over that they can be used to advantage by the Alaska Branch of the Geological Survey in filling in the inaccessible glacier-covered areas on its topographic maps, with the aid of the Wilson photoalidade. Washburn's aerial surveys were made under the auspices, chiefly, of the National Geographic Society and the Harvard Institute of Geographic Exploration.

U. S. Geological Survey,
Washington, D. C.

## REPORT OF THE COMMITTEE ON ABSORPTION AND TRANSPIRATION, 1938-1939

### Charles H. Lee, Chairman

The personnel of the committee during the past year has included the following: H. F. Blaney; S. T. Harding; R. E. Horton; Charles H. Lee; B. E. Livingston; G. E. P. Smith; and W. N. White.

Individual members of the Committee have been active in their individual fields, but the activities of the Committee as a whole have been limited to compilation of references on absorption and transpiration for the "Bibliography of hydrology for the United States for the year 1938," which is published separately by the American Geophysical Union.

Among outstanding publications of the year is the "Report of the Rio Grande joint investigation in the Upper Rio Grande Basin in Colorado, New Mexico, and Texas, 1936-1937," issued by the National Resources Committee. Part III of that Report contains a very complete discussion of the consumptive use of water with application to the problems of the Upper Rio Grande Valley. Determinations of consumptive use were made for large areas and from tanks, and are analyzed with supplemental data on meteorology and soil. H. B. Blaney, a member of the Committee, participated in the preparation of the Report.

The Chairman, as a General Reporter for the meeting of 1939 of the International Association of Scientific Hydrology, also prepared a report with definitions of the different kinds of ground-water. This was done in collaboration with David G. Thompson and submitted to O. E. Meinzer, head of the International Commission on Underground Water. The paper will be presented at the Assembly in September, 1939, of the International Association in Washington, D. C.

A very interesting contribution to the subject of transpiration and associated losses from watersheds is the recent paper by Joseph Kittredge, Jr., on "The magnitude and regional distribution of water-losses influenced by vegetation" [J. Forestry, v. 36, No. 8, 1938]. A map accompanies the paper showing distribution of annual water-losses in the United States in inches as computed from an isohyetal map of mean annual precipitation and a map of mean annual runoff. Accompanying the map and based thereon is a table of annual water-losses in different forest-regions typical of the west and east. Results agree in general with data derived from other sources. The method would appear to be applicable to local areas where conditions of rainfall and runoff are reasonably uniform and sufficient data are available.

Among the research activities on absorption now in progress, that of the California Forest and Experiment Station, United States Forest Service, at Berkeley, California, is outstanding. Portable equipment has been developed for creating uniformly distributed artificial rain at controlled rates and for measuring the runoff therefrom in the field using small enclosed areas. The purpose is to determine the absorption-rates and limits of typical soils and topography on watersheds contributing to flood-flow of streams, as an aid in dèsign of flood-control works. The first attempt of this kind was made by engineers for the Miami Conservancy District in Ohio about 25 years ago. More recently the method with improved equipment was used by engineers for the Los Angeles County Flood-Control District. The equipment now being developed at Berkeley under the direction of P. B. Rowe, Associate Silviculturist, overcomes some of the limitations of previous efforts and gives promise of furnishing a practicable and reasonably dependable instrument for field-measurement of absorption of rainfall by land-areas.

58 Sutter Street,
San Francisco, California

## REPORT OF THE COMMITTEE ON RUNOFF, 1938-1939

W. G. Hoyt, Chairman

The personnel of the Committee has remained unchanged throughout the year.

H. K. Barrows
Merrill Bernard
E. S. Cullings
R. W. Davenport
R. S. Goodridge
R. E. Horton
I. E. Houk
W. G. Hoyt
Joseph Jacobs
F. T. Mavis
A. F. Meyer
C. R. Pettis
F. F. Snyder
H. C. Troxell
C. W. Wisler

Individually, members of the Committee through personal study, research, and active participation on various committees of the Section of Hydrology and other organizations have advanced materially our knowledge of the phenomena of runoff and stream flow. Mr. Sherman as President of the Section has been a continued source of help and inspiration. Engineers and hydrologists in private practice, several from hydraulic laboratories, and personnel of the Soil Conservation Service, Forest Service, Weather Bureau, Corps of Engineers, Geological Survey, and other Federal agencies interested in the phenomena of runoff have attended and taken active part in the roundtable discussions of the Committee. To a very considerable extent it is believed that the roundtable discussions, although not made a part of the published "Transactions," have done much to promote a spirit of friendly and scientific cooperation.

The "Bibliography of Hydrology for the United States for the year 1938" prepared by Mr. Beij, and published separately by the American Geophysical Union, is so complete that inclusion in this Report of all references to articles relating to runoff seems unnecessary. In this connection, however, the Runoff Committee is deeply indebted to Miss Mary O. Soroka, of New York City, for her work in compiling complete references for the past year. Attention of the members of the Section may well be called to several reports and papers of particular interest. One is the Progress-Report of the Committee of the American Society of Civil Engineers on "Flood-protection data" [Proc. Amer. Soc. Civil Eng., January 1939], which discusses the adequacy of flood-data and points out certain limitations inherent in statistical analyses of flood-events. Another paper of particular interest is one by Otto H. Meyer relating to new developments in the unit-hydrograph [Proc. Amer. Soc. Civil Eng., November, 1938]. A third paper, that by Colonel Pettis, a member of the Runoff Committee, relates to hydrology of the Great Lakes and was published in April [Proc. Amer. Soc. Civil Eng., April, 1938]. Colonel Pettis' paper is of special interest to hydrologists in that its findings are considerably at variance with accepted hydrologic theory with reference to the magnitude of land-losses and ground-water flow. These papers are still open for discussion. During the year the Geological Survey has published two comprehensive reports on floods: Water-Supply Paper 816 on the "Major Texas floods of 1936," and Water-Supply Paper 838 on "Floods of the Ohio and Mississippi River, January - February 1937." Similar reports are in course of preparation relating to the Pecos Flood of June 1937, the Muskingum Flood of August 1935, major Texas floods of 1935, northern California Flood of December 1937, southern California Flood of March 1938, and the hurricane-floods of September 1938 in New England. The 750-page report treating of floods of the Ohio and Mississippi River, January and February 1937, is particularly exhaustive, containing as it does all available information relating to meteorologic conditions and precipitation-measurements, stage and river-discharges, records of previous floods, analyses of rainfall and runoff, and studies of channel-storage. The report also contains a section on flood-deposition in the Ohio River Valley based on a field-examination made for the purpose of determining the probable magnitude of flood-stages in the Ohio River Valley from geologic evidence. During the past year a Subcommittee of the Water Resources Committee of the National Resources Committee prepared a manual on low dams. This report contains two appendixes of immediate interest to the Section of Hydrology: Appendix A by Merrill Bernard entitled "Modified rational method of estimating flood flows;" and Appendix I by C. S. Jarvis entitled "Average and maximum river discharges." The report also contains a map of the United States on which has been plotted the Myers rating for the maximum flood-flows.

As Appendix A to the Report of the Runoff Committee, R. S. Goodridge has prepared a description of observations of rainfall, runoff, and sedimentation being carried on by the Soil Conservation Service through the Section of Soil and Water Conservation Experimental Farms, the Section of Watershed and Hydrologic Studies, and the Section of Sedimentation Studies. The location and size of about 250 areas or basins, the great majority of which are measured in terms of acres rather than square miles, are included in this tabulation. It is expected that eventually a similar tabulation will be available for areas in watersheds on which the Forest Service are conducting studies of rainfall, runoff, and sedimentation. In addition, the University of Iowa is continuing its hydrologic studies in the Ralston Creek and Rapid Creek watersheds. During the year the United States Geological Survey, in cooperation with Federal agencies, states, municipalities, and other organizations, has maintained 3900 stations on rivers, lakes, and reservoirs of which about 3000 are equipped with continuous water-stage recorders. Each river-basin in which there are continuous observations of stream-flow and meteorologic phenomena constitutes a potential laboratory for hydrologic investigations. The importance of this laboratory must not be overlooked in our present-day intensified studies of hydrologic phenomena.

To a greater or less extent, experimental studies are being conducted by the Tennessee Valley Authority, Los Angeles County Flood-Control District, the City of Los Angeles, Muskingum Conservancy District, Miami Conservancy District, universities, cities, and others. In many instances, however, the basic data are being collected by Federal agencies.

There is some question to what extent the Runoff Committee of the Section should function as a clearing house in connection with these research activities. It has been suggested that an annual report on the significant findings and activities of the various investigators, not otherwise available to the members, might properly be a function of the Runoff Committee. There is no doubt that the Section of Hydrology through the Runoff Committee should be in a position to render constructive criticism, advice, and otherwise to cooperate in the wide-spread and comprehensive hydrologic studies now in progress.

U. S. Geological Survey,
Washington, D. C.

## APPENDIX A--OBSERVATIONS OF RAINFALL, RUNOFF, AND SEDIMENTATION OF UNITED STATES SOIL CONSERVATION SERVICE

R. S. Goodridge

Following are data on watersheds and fields with supplementary plots and lysimeters for surface-runoff, operated by the Soil Conservation Service through its Division of Research or as designated in cooperation with the United States Geological Survey. Tables 1 to 10 show that hydrologic research is being conducted on surface-areas covering a wide range. The size of the areas varies from approximately 700 square miles to a few square feet in area for lysimeters.

Conservation Experiment Stations Division--This Division is making surface-runoff measurements on 27 experimental farms distributed in 20 States and on which are made measurements of hydrologic factors as follows: (1) On about 50 small watersheds or fields from 3/4 to 68 acres; (2) on about 170 terraces from approximately 0.05 to seven acres; (3) on about 560 plots ranging in size from 0.005 to two acres.

Thirty of the small-plot areas are equipped to provide an accurate rate of surface-runoff and others are being equipped similarly as rapidly as possible. The same Division is conducting studies on infiltration from approximately 16 centers in the country. A summary tabulation is shown on Table 1. As an illustration descriptive of the extent and type of area upon which the work is done, Tables 2, 3, and 4 are added for stations at Guthrie (Oklahoma), Temple (Texas), and Zanesville (Ohio).

Hydrologic Division--This Division makes surface-runoff measurements on three experimental watersheds, the largest of which is about 5700 acres, located at Waco (Texas). Table 5 shows the characteristics of sub-drainages at Coshocton (Ohio), Table 6 at Waco (Texas), and Table 7 at Hastings (Nebraska). This Division, in addition, conducts cooperatively with Technical Operations of the Service measurements on 93 small watersheds, distributed among 19 States, and summarized in Table 8. Also, in cooperation with the United States Geological Survey, gaging is being conducted in four regions, as shown in Table 9.

Table 1--Surface runoff-measurements by Soil Conservation Service, Divisions of Research, Conservation Experiment Stations Division

| Item No. | State | Town | Watersheds and fields, area in acres by units | | | | | Terraces No. | Plots No. | Lysimeters | Record begun |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 4 | 5 | | | | |
| 1 | Arkansas | Batesville | .... | .... | .... | .... | .... | .. | 14 | .. | 1939 |
| 2 | Georgia | Athens | .... | .... | .... | .... | .... | .. | 18 | .. | 1939 |
| 3 | Illinois | Dixon Springs | .... | .... | .... | .... | .... | .. | 29 | .. | 1938 |
| 4 | Iowa | Clarinda | 3.25 | 3.25 | 3.12 | 1.97 | 1.97 | 22 | 23 | 24 | 1932 |
| 5 | Kansas | Hays | 2.85 | 2.71 | 1.61 | 1.03 | 0.91 | 11 | 35 | .. | 1930 |
| | | | 0.88 | 0.85 | 0.85 | 0.85 | 0.76 | .. | .. | .. | .... |
| 6 | Louisiana | Baton Rouge | .... | .... | .... | .... | .... | .. | 12 | .. | 1939 |
| 7 | Maine | Presque Isle | .... | .... | .... | .... | .... | .. | 12 | .. | 1939 |
| 8 | Missouri | Bethany | 8.03 | 7.51 | 5.56 | 4.85 | 2.13 | 23 | 43 | .. | 1931 |
| | | | 2.12 | 2.11 | 1.97 | 1.43 | .... | .. | .. | .. | .... |
| 9 | Missouri | McCredie | .... | .... | .... | .... | .... | .. | 15 | .. | 1939 |
| 10 | New Jersey | Beemerville | .... | .... | .... | .... | .... | .. | 12 | .. | 1937 |
| 11 | New Jersey | Marlboro | .... | .... | .... | .... | .... | .. | 24 | .. | 1938 |
| 12 | New Mexico | Mexican Springs | 187 | 610 | 1325. | 2550. | 3360. | .. | .. | .. | 1936 |
| | | | 3560 | 4235 | 4510. | 4740. | 5550. | | | | |
| | | | 8490 | 17220. | 20910. | 46080. | .... | | | | |
| 13 | New York | Geneva | .... | .... | .... | .... | .... | .. | 8 | .. | 1936 |
| 14 | New York | Hammondsport | .... | .... | .... | .... | .... | .. | 4 | .. | 1935 |
| 15 | New York | Ithaca | .... | .... | .... | .... | .... | .. | 44 | .. | 1935 |
| 16 | New York | Marcellus | .... | .... | .... | .... | .... | .. | 13 | .. | 1939 |
| 17 | North Carolina | Statesville | 6.01 | 5.12 | .... | .... | .... | 20 | 26 | 6 | 1931 |
| 18 | Ohio | Zanesville | 3.57 | 2.55 | 2.23 | 0.81 | 0.79 | 20 | 26 | .. | 1933 |
| 19 | Oklahoma | Guthrie | 35.0 | 5.62 | 5.28 | 3.21 | 3.13 | 16 | 21 | .. | 1929 |
| | | | 2.50 | .... | .... | .... | .... | | | | |
| 20 | Pennsylvania | State College | .... | .... | .... | .... | .... | .. | 49 | .. | 1935 |
| 21 | South Carolina | Spartanburg | .... | .... | .... | .... | .... | .. | 12 | .. | 1936 |
| 22 | Texas | Spur | 1200 | 102 | 10 | 10 | .... | .. | 8 | .. | 1926 |
| 23 | Texas | Temple | 2.23 | 2.23 | .... | .... | .... | 18 | 25 | 12 | 1930 |
| 24 | Texas | Tyler | 7.94 | 5.75 | 1.57 | .... | .... | 22 | 33 | .. | 1930 |
| 25 | Vermont | Burlington | .... | .... | .... | .... | .... | .. | 9 | .. | 1938 |
| 26 | Washington | Pullman | 16704. | 762. | 68.2 | 15.2 | 14.4 | 12 | 21 | .. | 1931 |
| | | | 2.33 | .... | .... | .... | .... | | | | |
| 27 | Wisconsin | La Crosse | 2.71 | 2.41 | 2.34 | .... | .... | 9 | 47 | 12 | 1932 |

Sedimentation Division--This Division is operating the project generally known as the "Bed-load Project." While designed primarily for the study of transportation of erosional debris by natural streams, these studies will produce some very valuable runoff-data, correlated with the rainfall on watersheds and the distribution of erosional debris in the watersheds, as aptly described in the official designation of the project, "Investigations of the amounts and factors affecting occurrence and movement of sediment in natural streams."

Especially designed controls have been installed on three natural streams in the Southeastern Piedmont Region, as shown in Table 10. These controls are designed to permit hydraulic removal of bed-load from any portion of the bottom of the river. Data on suspended load and the hydraulic functions of the stream will be obtained by standard methods and will be related to natural reaches upstream from the controls.

Construction at these three sites has been completed but only the control on the Enoree River, near Greenville (South Carolina), is now being operated. This control is installed on a rock-foundation. The bottom of the River is paved with concrete, the sides consisting of vertical concrete retaining walls, which give the reshaped section the form of a rectangle designed to have the same discharge-capacity as the replaced natural section for the expected maximum flood. The section is 83 feet wide, divided into 14 sub-channels of five feet clear width, separated by one-foot concrete vane walls three feet high. The intakes are horizontal gates at the bottom of the River operated hydraulically from the control-house. The samples are pumped through the intake openings which connect with a 16-inch master pipe-line under the bed of the River into a separating tank. The sediment is removed, weighed, and analyzed.

Table 2--Watersheds, fields, terraces, and plots for runoff-measurements by Soil Conservation Service, Conservation Experiment Stations Division, Guthrie, Oklahoma, 1937

| Item No. | Ident. No. | Kind of study (see note 2 for size) | Area, acres | Slope-per cent exposure | Record begun | Type gaging (see note 3) |  | No. rain-gages |  | Dominant soil-texture (see note 1) | Land-use (see note 4) |
|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  |  | Run-off | Sedi-ment | Re-cording | Stan-dard |  |  |
|  |  | CONTROL-PLOTS |  |  |  |  |  |  |  |  |  |
| 1 | 1 | Effect of length of slope (A) | 0.005 | 7.70 E | 1929 | B | B | 1 | 1 | ... | Con co |
| 2 | 2 | Effect of length of slope (B) | 0.02 | 7.70 E | 1929 | B | B | 1 | 1 | ... | Con co |
| 3 | 3 | Effect of length of slope (C) | 0.01 | 7.70 E | 1929 | B | B | 1 | 1 | ... | Con co |
| 4 | 4 | Crop-rotation (C) | 0.01 | 7.70 E | 1929 | B | B | 1 | 1 | ... | Ro:wh,swcl,co |
| 5 | 5 | Crop-rotation (C) | 0.01 | 7.70 E | 1929 | B | B | 1 | 1 | ... | Ro:swcl,co,wh |
| 6 | 6 | Crop-rotation (C) | 0.01 | 7.70 E | 1929 | B | B | 1 | 1 | ... | Ro:co,wh,swcl |
| 7 | 7 | Pasture, grass (C) | 0.01 | 7.70 E | 1929 | B | B | 1 | 1 | ... | Gr,Ber |
| 8 | 8 | Hard, bare fallow (C) | 0.01 | 7.70 E | 1929 | B | B | 1 | 1 | ... | Bare |
| 9 | 9 | Erosion (C) | 0.01 | 7.70 E | 1929 | B | B | 1 | 1 | (c) | Con co |
| 10 | 10 | Native woods (C) | 0.01 | 5.17 S | 1930 | B | B | 1 | 1 | ... | Owv |
| 11 | 11 | Burned annually (C) | 0.01 | 5.17 S | 1930 | B | B | 1 | 1 | ... | Owb |
| 12 | 12 | Fall plowing and cultivation (C) | 0.01 | 6.06 S | 1931 | B | B | 1 | 1 | ... | Co |
| 13 | 13 | Grass, Bermuda and native (C) | 0.01 | 5.17 S | 1933 | B | B | 1 | 1 | ... | Gr |
|  |  | MISCELLANEOUS PLOTS |  |  |  |  |  |  |  |  |  |
| 14 | SC-1 | Hole digging cultivation (D) | 0.25 | 3.77 NW | 1934 | G | G | 1 | 1 | (e) | Co,wh cov |
| 15 | SC-2 | Ordinary cultivation (D) | 0.25 | 3.77 NW | 1934 | G | G | 1 | 1 | (e) | Co,wh cov |
| 16 | RD-1 | Row direction, slope (D) | 0.25 | 6.75 E | 1932 | 90°V | B | 1 | 1 | (e) | Co,wh cov |
| 17 | RD-2 | Row direction, contour (D) | 0.25 | 6.87 E | 1932 | 90°V | B | 1 | 1 | ... | Co,wh cov |
| 18 | StC-1 | Strip-cropping, contour (E) | 1.00 | 4.50 S | 1934 | G | G | 1 | 1 | ... | Al,co |
| 19 | StC-2 | Strip-cropping, contour (E) | 1.00 | 4.00 S | 1934 | G | G | 1 | 1 | (c) | O to S,co,wh cov |
| 20 | StC-3 | Continuous cotton, contour (E) | 1.00 | 3.50 SE | 1934 | G | G | 1 | 1 | ... | Co |
| 21 | StC-4 | Strip-cropping, contour (E) | 1.00 | 3.00 SW | 1934 | G | G | 1 | 1 | (e) | O to wh cov, o to S |
|  |  | TERRACES (Study of terrace-spacing) |  |  |  |  |  |  |  |  |  |
|  |  | Long feet · Vert. feet · Wide feet · Grade per cent · Rise feet |  |  |  |  |  |  |  |  |  |
| 22 | 1-A | 700 · 2.0 · 37 · 0.33 · 1.23 | 0.594 | 5.35 SSE | 1930 | P | R | 1 | 1 | ... | Ro:co,wh,o,cwp |
| 23 | 2-A | 700 · 3.5 · 65 · 0.33 · 1.05 | 1.052 | 5.60 SSE | 1930 | P | R | 1 | 1 | ... | Ro:co,wh,o,cwp |
| 24 | 3-A | 700 · 5.0 · 92 · 0.33 · 1.03 | 1.485 | 5.45 SSE | 1930 | P | R | 1 | 1 | ... | Ro:co,wh,o,cwp |
| 25 | 4-A | 700 · 5.0 · 89 · 0.33 · 0.96 | 1.438 | 5.58 SSE | 1930 | P | R | 1 | 1 | ... | Ro:co,wh,o,cwp |
| 26 | 5-A | 700 · 3.5 · 61 · 0.33 · 1.025 | 0.976 | 5.76 SSE | 1930 | P | R | 1 | 1 | ... | Ro:co,wh,o,cwp |
| 27 | 6-A | 700 · 2.0 · 37 · 0.33 · 1.31 | 0.595 | 5.60 SSE | 1930 | P | R | 1 | 1 | ... | Ro:co,wh,o,cwp |

Table 2--Watersheds, fields, terraces, and plots for runoff-measurements by Soil Conservation Service, Conservation Experiment Stations Division, Guthrie, Oklahoma, 1937--Concluded

| Item No. | Ident. No. | Kind of study (see note 2 for size) | Area, acres | Slope-per cent exposure | Record begun | Type gaging (see note 3) | | No. rain-gages | | Dominant soil-texture (see note 1) | Land-use (see note 4) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Run-off | Sedi-ment | Re-cording | Stan-dard | | |
| | | TERRACES (Study of terrace-grades) | | | | | | | | | |
| 28 | 2-B | 2536 3.99 103 0-0.33 1.32 | 5.99 | 2.79 W | 1931 | P | R | 1 | 2 | ... | Ro:co,wh,o,cwp |
| 29 | 3-B | 2856 3.45 86 0-0.50 1.20 | 5.67 | 4.21 W | 1931 | P | R | 1 | 3 | ... | Ro:co,wh,o,cwp |
| 30 | 4-B | 2885 3.98 84 0.25 1.24 | 5.58 | 4.21 W | 1931 | P | R | 1 | 4 | ... | Ro:co,wh,o,cwp |
| 31 | 1-C | 2350 3.91 114 0-0.33 1.30 | 6.16 | 3.54 E | 1931 | P | R | 1 | 2 | ... | Ro:co,wh,o,cwp |
| 32 | 2-C | 2525 2.93 75 0-0.50 1.20 | 4.37 | 3.66 E | 1932 | P | R | 1 | 4 | ... | Ro:co,wh,o,cwp |
| 33 | 3-C | 1500 3.51 83 0.50 1.21 | 2.85 | 4.33 E | 1931 | P | R | 1 | 3 | ... | Ro:co,wh,o,cwp |
| 34 | 4-C | 1500 3.47 80 0.33 1.27 | 2.77 | 4.41 E | 1930 | P | R | 1 | 3 | ... | Ro:co,wh,o,cwp |
| 35 | 5-C | 1500 3.43 75 0.17 1.10 | 2.578 | 4.72 E | 1930 | P | R | 1 | 2 | ... | Ro:co,wh,o,cwp |
| 36 | 6-C | 1500 3.27 60 Level 1.07 | 2.06 | 5.51 E | 1931 | P | R | 1 | 2 | ... | Ro:co,wh,o,cwp |
| 37 | 6-E | 648 4.00 81 Level 1.05 | 1.20 | 4.85 W | 1933 | P | R | 1 | 2 | (e) | Ro:co,wh,cwp |
| | | WATERSHEDS AND FIELDS | | | | | | | | | |
| 38 | Ravine A | Terraced, cultivated land | 35.0 | 4.94 W-S | 1931 | P | None | 3 | 4 | (e) | Co,cl,wh,gr,w |
| 39 | Plot 13 | Unterraced, cultivated land | 3.23 | 5.13 W | 1931 | P | R | 1 | 1 | (e) | Ro:co,wh,cwp |
| 40 | Plot 15 | A level terraced watershed--four level terraces | 3.13 | 3.42 W | 1930 | P | R | 1 | 2 | (e) | Ro:co,wh,cwp |
| 41 | Pas.plot | Grassed watershed (pasture-plot) | 2.50 | 5.65 NW | 1933 | P | R | 1 | 1 | ... | Native gr |
| 42 | Plot L | Wooded watershed | 5.62 | 4.80 SW | 1930 | P | R | 1 | 1 | ... | Native w |
| 43 | Plot J | Gullied, grassed area | 5.28 | 4.44 SE | 1930 | P | None | 1 | 2 | (e) | Native gr |

Notes: (1) Dominant soil-texture in all cases is Vernon, fine, sandy loam, except where otherwise marked by (c) which indicates Vernon, fine, sandy clay-loam; for entries indicated by (e) plots are eroded.

(2) Under kind of study, dimensions of plots are: (A), 6 by 36.3 feet; (B) 6 by 145.2 feet; (C) 6 by 72.6 feet; (D) 60 by 181.5 feet; (E) 128 by 340.3 feet.

(3) Type gaging indicated by P for Parshall, B for basin, R for Ramser, and G for Geib

(4) Under land-use following abbreviations are used: Con = continuous; ro = rotation; al = alfalfa; cl = clover; co = cotton; cov = cover; cr = corn; cwp = cowpeas; gr = grass (Ber = Bermuda, S = Sudan); o = oats; owv = oak woods, virgin; owb = oak woods, burned; per = permanent; swcl = sweet clover; v = vetch; w = woods; wh = wheat.

Table 3--Watersheds, fields, terraces, and plots for runoff-measurements by Soil Conservation Service, Conservation Experiment Stations Division, Temple, Texas, 1937

| Item No. | Ident. No. | Kind of study (see note 3 for size) | Area, acres | Slope-per cent exposure | Record begun | Type gaging (see note 2) |  | No. rain-gages |  | Dominant soil-texture (see note 1) | Land-use (see note 4 of Table 2) |
|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  |  | Run-off | Sedi-ment | Re-cording | Stan-dard |  |  |
|  |  | CONTROL-PLOTS |  |  |  |  |  |  |  |  |  |
| 1 | 1 | Slope-length (A) | 0.005 | 4 E | 1930 | B | B | 1 | 1 | ..... | Con cr |
| 2 | 2 | Slope-length (B) | 0.02 | 4 E | 1930 | B | B | 1 | 1 | ..... | Con cr |
| 3 | 3 | Slope-length (C) | 0.01 | 4 E | 1930 | B | B | 1 | 1 | ..... | Con cr |
| 4 | 4 | Rotation green manure (C) | 0.01 | 4 E | 1930 | B | B | 1 | 1 | ..... | Ro:cr,o,co |
| 5 | 5 | Rotation contour tillage (C) | 0.01 | 4 E | 1930 | B | B | 1 | 1 | ..... | Ro:cr,o,co |
| 6 | 6 | Vegetative control (C) | 0.01 | 4 E | 1930 | B | B | 1 | 1 | ..... | Ber gr |
| 7 | 7 | Rotation green manure (C) | 0.01 | 4 E | 1930 | B | B | 1 | 1 | ..... | Ro:cr,o,co |
| 8 | 8 | Rotation green manure (C) | 0.01 | 4 E | 1930 | B | B | 1 | 1 | ..... | Ro:cr,o,co |
| 9 | 9 | Rotation green manure (C) | 0.01 | 4 E | 1930 | B | B | 1 | 1 | ..... | Ro:o,co,cr |
| 10 | 10 | Rotation contour green manure (C) | 0.01 | 4 E | 1930 | B | B | 1 | 1 | ..... | Ro:cr,o,co |
| 11 | 11 | Severe erosion green manure (C) | 0.01 | 4 E | 1930 | B | B | 1 | 1 | (S) | Ro:cr,o,co |
|  |  | STRIP-CROPPED |  |  |  |  |  |  |  |  |  |
| 12 | 12 | Strip-cropping (F) | 0.046 | 3.5 E | 1932 | G | G | 1 | 1 | ..... | S,co,o,after co |
| 13 | 13 | Contouring (G) | 0.085 | 3.5 E | 1932 | G | G | 1 | 1 | ..... | Con co |
| 14 | 14 | Rows down slope (H) | 0.031 | 3.5 E | 1932 | G | G | 1 | 1 | ..... | Con co |
| 15 | 15 | Strip-cropping (G) | 0.085 | 3.5 E | 1932 | G | G | 1 | 1 | ..... | 24 ft-S,co,v af.S |
| 16 | 16 | Strip-cropping (I) | 0.05 | 3.5 E | 1932 | G | G | 1 | 1 | ..... | 24 ft-o,co,v af.o |
| 17 | 17 | Rows on contour (J) | 0.0505 | 2 W | 1933 | G | G | 1 | 1 | ..... | 30 ft-S followed by o,co |
| 18 | 18 | Vegetative control (K) | 0.0286 | 2 W | 1933 | G | G | 1 | 1 | ..... | Con Ber gr |
| 19 | 19 | Rotation (K) | 0.0286 | 2 W | 1933 | G | G | 1 | 1 | ..... | Ro:cr,o,co |
| 20 | 20 | Rotation (K) | 0.0286 | 2 W | 1933 | G | G | 1 | 1 | ..... | Ro:cr,o,co |
| 21 | 21 | Rotation (K) | 0.0286 | 2 W | 1933 | G | G | 1 | 1 | ..... | Ro:cr,o,co |
| 22 | 22 | Rows down slope (K) | 0.0286 | 2 W | 1933 | G | G | 1 | 1 | ..... | Con cr |
| 23 | 23 | Strip-cropping (L) | 1.38 | 4-6 E | 1933 | G | G | 1 | 1 | (H-c) | O,co |
| 24 | 24 | Strip-cropping, rows down slope | 0.137 | 4-6 E | 1933 | G | G | 1 | 1 | (H-c) | Con co |
| 25 | 25 | Strip-cropping, rows on contour | 1.39 | 4-6 E | 1933 | G | G | 1 | 1 | (H-c) | Con co |
|  |  | FIELDS |  |  |  |  |  |  |  |  |  |
| 26 | F | Contour-rows (M) | 2.227 | 2.5 E | 1931 | P | R | 1 | 1 | (H-B) | Ro:o,cr |
| 27 | G | Rows down slope (M) | 2.226 | 2.5 E | 1931 | P | R | 1 | 2 | (H-B) | Ro:o,cr |

Table 3--Watersheds, fields, terraces, and plots for runoff-measurements by Soil Conservation Service, Conservation Experiment Stations Division, Temple, Texas, 1937--Concluded

| Item No. | Ident. No. | Kind of study (see note 3 for size) | | | | | Area, acres | Slope-per cent exposure | Record begun | Type gaging (see note 2) | | No. rain-gages | | Dominant soil-texture (see note 1) | Land-use (see note 4 of Table 2) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | Run-off | Sedi-ment | Re-cording | Stan-dard | | |
| | | TERRACES (Effect of different crops) | | | | | | | | | | | | | |
| | | Long feet | Vert. feet | Wide feet | Grade per cent | Rise feet | | | | | | | | | |
| 28 | A-13 | 892 | 2 | 70.1 | 0.25 | 1.66 | 1.40 | 3.1 W | 1930 | P | R | 1 | 1 | (H-c, bl c) | Ro:cr,o,cr,co |
| 29 | A-14 | 897 | 1.7 | 64.7 | 0.25 | 1.45 | 1.28 | 2.6 W | 1930 | P | R | 1 | 1 | (H-c, bl c) | Ro:co,o,cr,o |
| 30 | A-15 | 905 | 2.3 | 63.3 | 0.25 | 1.73 | 1.24 | 3.6 W | 1930 | P | R | 1 | 2 | (H-c, bl c) | Ro:co,cr,co,o |
| | | (Terrace-spacing) | | | | | | | | | | | | | |
| 31 | A-16 | 896 | 3 | 90.4 | 0.25 | 1.75 | 1.74 | 3.1 W | 1930 | P | R | 1 | 2 | (H-c, bl c) | Ro:co,cr,co,o |
| 32 | A-17 | 749 | 4 | 129.5 | 0.25 | 1.75 | 2.07 | 3.1 W | 1930 | P | R | 1 | 2 | (H-c, bl c) | Ro:co,cr,co,o |
| | | (Spacing, length, and minimum grades) | | | | | | | | | | | | | |
| 33 | A-18 | 625 | 2.6 | 82.1 | 0.08 | 1.64 | 1.14 | 3.2 W | 1930 | P | R | 1 | 2 | ..... | Ro:co,cr,co,o |
| 34 | A-19 | 625 | 2.8 | 109.1 | 0.08 | 1.56 | 1.55 | 2.6 W | 1930 | P | R | 1 | 2 | ..... | Ro:co,cr,co,o |
| 35 | A-20 | 625 | 2.7 | 137.1 | 0.08 | 1.60 | 1.90 | 2.0 W | 1930 | P | R | 1 | 2 | ..... | Ro:co,cr,co,o |
| | | (Spacing and length of level terraces) | | | | | | | | | | | | | |
| 36 | B-3 | 847 | 3 | 75.8 | Level | 1.65 | 1.35 | 4.0 W | 1931 | P | R | 1 | 1 | ..... | Ro:co,cr,co,o |
| 37 | B-4 | 938 | 2 | 49.6 | Level | 1.45 | 1.016 | 4.0 W | 1934 | P | R | 1 | 1 | ..... | Ro:co,cr,co,o |
| | | (Terrace-spacing on a 5.4 per cent slope) | | | | | | | | | | | | | |
| 38 | C-5 | 850 | 3 | 52.9 | 0.25 | 1.54 | 1.04 | 5.4 E | 1930 | P | R | 1 | 2 | (H-c, bl c) | Ro:co,cr,co,o |
| 39 | C-6 | 844 | 4 | 74.6 | 0.25 | 1.45 | 1.47 | 5.4 E | 1930 | P | R | 1 | 2 | (H-c, bl c) | Ro:co,cr,co,o |
| 40 | C-7 | 828 | 5 | 94.1 | 0.25 | 1.57 | 1.83 | 5.4 E | 1930 | P | R | 1 | 2 | (H-c, bl c) | Ro:co,cr,co,o |
| | | (Terrace-grades and maximum lengths) | | | | | | | | | | | | | |
| 41 | C-13 | 1930 | 3.9 | 90.1 | 0-0.25 | 1.61 | 3.94 | 4.4 E | 1930 | P | R | 1 | 3 | (H-c, bl c) | Ro:co,cr,co,o |
| 42 | C-14 | 1875 | 3.8 | 92.7 | 0.25 | 1.67 | 4.05 | 4.1 E | 1931 | P | R | 1 | 3 | (H-c, bl c) | Ro:co,cr,co,o |
| 43 | C-15 | 1856 | 2.8 | 79.9 | 0.33 | 1.64 | 3.44 | 3.6 E | 1931 | P | R | 1 | 3 | (H-c, bl c) | Ro:co,cr,co,o |
| 44 | C-16 | 1870 | 2.8 | 91.9 | 0.42 | 1.58 | 3.96 | 3.1 E | 1931 | P | R | 1 | 3 | (H-c, bl c) | Ro:co,cr,co,o |
| 45 | C-17 | 1890 | 2.9 | 91.2 | 0-0.42 | 1.54 | 3.78 | 3.2 E | 1931 | P | R | 1 | 3 | (H-c, bl c) | Ro:co,cr,co,o |

Notes: (1) Dominant soil-texture in all cases is Houston black clay, except as follows: (H-c) = Houston clay; (H-c, bl c) = Houston clay, black clay; (S) = Sumpter sandy clay; (H-B) = Houston and Bell clay.

(2) Type gaging indicated by P for Parshall, B for basin, R for Ramser, and G for Geib.

(3) Under kinds of study, dimensions of plot are: (A) 6 by 36.3 feet; (B) 6 by 145.2 feet; (C) 6 by 72.6 feet; (D) 60 by 181.5 feet; (E) 128 by 340.3 feet; (F) 12 by 168 feet; (G) 22 by 168 feet; (H) 8 by 168 feet; (I) 13 by 168 feet; (J) 17 by 129.5 feet; (K) 9 by 138.35 feet; (L) 200 by 300 feet; (M) 175 by 554.3 feet.

Table 4--Watersheds, fields, terraces, and plots for runoff-measurements by Soil Conservation Service, Conservation Experiment Stations Division, Zanesville, Ohio

| Item No. | Ident. No. | Kind of study (see note 3 for size) | Area, acres | Slope per cent exposure | Record begun | Type gaging (see note 2) |  | No. rain-gages |  | Dominant soil-texture (see note 1) | Land-use (see note 4 of Table 2) |
|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  |  | Run-off | Sedi-ment | Re-cording | Stan-dard |  |  |
|  |  |  |  | WATERSHEDS |  |  |  |  |  |  |  |
| 1 | ... | Cultivated, 3-year rotation | 2.55 | 14 SE | 1933 | P | R | 1 | 1 | (M-E) | Ro:cr,wh,gr |
| 2 | ... | Pasture, fertilized, limed | 3.57 | 14 SE | 1933 | P | R | 1 | 2 | (M-1) | Per pasture |
| 3 | ... | Wooded, hardwood, second growth | 2.23 | 14 S,SW | 1933 | P | R | 1 | 1 | (M) | Per w |
|  |  |  |  | FIELDS |  |  |  |  |  |  |  |
|  |  | No. Width |  |  |  |  |  |  |  |  |  |
| 4 | A | Strip-cropping, 3-year rotation (3) 62-78 ft | 0.49 | 14-16 N | 1935 | P | R | 1 | 3 | (M) | Ro:cr,wh,gr |
| 5 | B | Strip-cropping, 3-year rotation (3) 73-78 ft | 0.49 | 14-16 N | 1935 | P | R | 1 | 3 | (M) | Ro:cr,wh,gr |
| 6 | C | Strip-cropping, 4-year rotation (4) 66-68 ft | 0.495 | 14-16 E | 1935 | P | R | 1 | 3 | (M) | Ro:cr,wh,cr,gr |
| 7 | D | Strip-cropping, 4-year rotation (4) 66-68 ft | 0.502 | 14-16 E | 1935 | P | R | 1 | 3 | (M) | Ro:cr,wh,cr,gr |
| 8 | E | Width of strip, 3-year rotation (3) 70 ft | 0.792 | 14-15 S | 1935 | P | R | 1 | 3 | (M) | Ro:cr,wh,gr |
| 9 | F | Width of strip, 3-year rotation (6) 35 ft | 0.809 | 14-15 S | 1935 | P | R | 1 | 3 | (M) | Ro:cr,wh,gr |
|  |  |  |  | TERRACES<br>(Grades and lengths) |  |  |  |  |  |  |  |
|  |  | Long feet / Vert. feet / Wide feet / Grade per cent / Rise feet |  |  |  |  |  |  |  |  |  |
| 10 | A-3 | 1200 / 7.0 / 62 / 0.08-0.50 / 0.7 | 1.699 | 12 SE | 1933 | P | R | 1 | 5 | (M) (e) | Ro:cr,wh,gr |
| 11 | A-4 | 1187 / 7.0 / 45 / 0.08-0.25 / 0.75 | 1.238 | 12 SE | 1933 | P | R | 1 | 5 | (M) (e) | Ro:cr,wh,gr |
| 12 | A-5 | 718 / 7.0 / 45 / Level / 0.95 | 0.742 | 12 SE | 1933 | P | R | 1 | 5 | (M) (e) | Ro:cr,wh,gr |
| 13 | A-6 | 747 / 7.0 / 51 / 0.08-0.25 / 1.0 | 0.872 | 12 SE | 1933 | P | R | 1 | 5 | (M) (e) | Ro:cr,wh,gr |
| 14 | A-7 | 762 / 7.0 / 54 / 0.25 / 0.95 | 0.937 | 12 SE | 1933 | P | R | 1 | 5 | (M) | Ro:cr,wh,gr |
| 15 | A-8 | 736 / 7.0 / 59 / 0.17-0.50 / 1.0 | 1.003 | 12 SE | 1933 | P | R | 1 | 5 | (M) (e) | Ro:cr,wh,gr |
| 16 | A-10 | 1238 / 7.0 / 52 / 0.50 / 1.05 | 1.483 | 12 SESSW | 1933 | P | R | 1 | 5 | (M-E) | Ro:cr,wh,gr |
| 17 | A-11 | 1276 / 7.0 / 49 / 0.25 / 0.95 | 1.446 | 12 SESSW | 1933 | P | R | 1 | 5 | (M-E) | Ro:cr,wh,gr |
| 18 | A-12 | 1173 / 7.0 / 58 / Level / 1.3 | 1.573 | 12 SESSW | 1933 | P | R | 1 | 5 | (M-E) | Ro:cr,wh,gr |
|  |  |  |  | (Crop rotation) |  |  |  |  |  |  |  |
| 19 | A-13 | 808 / 7.0 / 63 / 0.25 / 1.5 | 1.176 | 10 SSW | 1933 | P | R | 1 | 5 | (M-E) | Ro:cr,wh,gr |
| 20 | A-14 | 810 / 7.0 / 62 / 0.25 / 0.8 | 1.157 | 10 SSW | 1933 | P | R | 1 | 5 | (M-E) | Ro:cr,wh,gr |
| 21 | A-15 | 848 / 7.0 / 65 / 0.25 / 1.15 | 1.26 | 10 SSW | 1933 | P | R | 1 | 5 | (M-E) | Ro:cr,wh,gr |
|  |  |  |  | (Spacing, grade, and pasture) |  |  |  |  |  |  |  |
| 22 | B-7 | 1148 / 10.0 / 66 / 0.08-0.50 / 1.4 | 1.74 | 12 NSESSW | 1933 | P | R | 1 | 5 | (M-E) | Pasture,seeded |
| 23 | B-8 | 1367 / 8.0 / 60 / 0-0.50 / 1.1 | 1.89 | 12 ESESSW | 1933 | P | R | 1 | 5 | (M-E) | Pasture,seeded |
| 24 | B-9 | 1098 / 8.0 / 66 / 0.12-0.75 / 1.0 | 1.66 | 12 ESSW | 1933 | P | R | 1 | 5 | (M-E) | Pasture,seeded |

Table 4--Watersheds, fields, terraces, and plots for runoff-measurements by Soil Conservation Service, Conservation Experiment Stations Division, Zanesville, Ohio--Concluded

| Item No. | Ident. No. | Kind of study (see note 3 for size) | Area, acres | Slope per cent exposure | Record begun | Type gaging (see note 2) |  | No. rain-gages |  | Dominant soil-texture (see note 1) | Land-use (see note 4 of Table 2 |
|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  |  | Run-off | Sedi-ment | Re-cording | Stan-dard |  |  |
|  |  | (Spacing, grade, and pasture) |  |  |  |  |  |  |  |  |  |
| 25 | C-3 | 1200 10.0 61 0.08-0.50 0.85 | 1.678 | 15 N | 1933 | P | R | 1 | 5 | (M-E) | Ro:cr,wh,gr |
| 26 | C-4 | 1200 8.0 51 0.08-0.50 0.85 | 1.410 | 15 N | 1933 | P | R | 1 | 5 | (M-E) | Ro:cr,wh,gr |
| 27 | C-5 | 1200 6.0 39 0.08-0.50 0.9 | 1.084 | 15 N | 1933 | P | R | 1 | 5 | (M-E) | Ro:cr,wh,gr |
| 28 | B-10 | 404 7.0 44 Level 0.8 | 0.404 | 12 SE | 1933 | P | R | 1 | 5 | (M) (e) | Pasture,seeded |
| 29 | B-11 | 478 7.0 43 Level 0.9 | 0.473 | 12 SE | 1933 | P | R | 1 | 5 | (M) (e) | Pasture,seeded |
|  |  | CONTROL-PLOTS |  |  |  |  |  |  |  |  |  |
| 30 | 1 | Length of slope (A), unfertilized | 0.005 | 12 S | 1933 | R-t | B | 1 | 2 | (M) | Con cr |
| 31 | 2 | Length of slope (B), unfertilized | 0.02 | 12 S | 1933 | R-t | B | 1 | 2 | (M) | Con cr |
| 32 | 3 | Length and degree of slope, unfertilized to compare with rotated and bare plots | 0.01 | 12 S | 1933 | R-t | B | 1 | 2 | (M) | Con cr |
| 33 | 4 | Rotation-experiment (C), unfertilized, limed | 0.01 | 12 S | 1933 | B | B | 1 | 2 | (M) | Cr,wh,gr,gr |
| 34 | 5 | Rotation-experiment (C), unfertilized, limed | 0.01 | 12 S | 1933 | B | B | 1 | 2 | (M) | Cr,wh,gr,gr |
| 35 | 6 | Rotation-experiment (C), unfertilized, limed | 0.01 | 12 S | 1933 | B | B | 1 | 2 | (M) | Cr,wh,gr,gr |
| 36 | 7 | Rotation-experiment (C), unfertilized, limed | 0.01 | 12 S | 1933 | B | B | 1 | 2 | (M) | Cr,wh,gr,gr |
| 37 | 8 | Comparison, normally eroded as against cultivated grassed cover (C), unfertilized, limed | 0.01 | 12 S | 1933 | B | B | 1 | 2 | (M) | Bare surface |
| 38 | 9 | Comparison, native grass to eroded cultivated grass (C), fertilized and limed | 0.01 | 12 S | 1933 | B | B | 1 | 2 | (M) | Native gr |
| 39 | 10 | Comparison, native grass to eroded cultivated grass (C), fertilized and limed | 0.01 | 12 S | 1933 | B | B | 1 | 2 | (M) | Blue-gr |
| 40 | 11 | Comparison, native grass to eroded cultivated grass (C), fertilized and limed | 0.01 | 12 S | 1933 | B | B | 1 | 2 | (M) | Blue-gr |
| 41 | 12 | Comparison, normally eroded to desurfaced soil (C), unfertilized but limed | 0.01 | 12 S | 1933 | B | B | 1 | 2 | (M) | Con cr |
| 42 | 13 | Comparison, fertilized vs. unfertilized cultivation (C), fertilized | 0.01 | 12 S | 1933 | B | B | 1 | 2 | (M) | Con cr |
| 43 | 14 | Degree of slope (C), unfertilized | 0.01 | 8 S | 1933 | B | B | 1 | 2 | (M) | Con cr |
| 44 | 15 | Degree of slope (C), unfertilized | 0.01 | 20 S | 1933 | B | B | 1 | 2 | (M) | Con cr |
|  |  | PASTURE-PLOTS |  |  |  |  |  |  |  |  |  |
| 45-49 | 1-5 | Pasture-cover (N) | 0.025 | 14 S | 1938 | T-G | G | 1 | 2 | (M) | Per pasture |

Notes: (1) Dominant soil-texture indicated by (M-E) for Muskigum and Elfort silt-loam, by (M) for Muskigum silt-loam, and by (M-1) for Muskigum loam; (e) indicates eroded.

(2) Type gaging indicated by P for Parshall, B for basin, R-t for rate-tank, R for Ramser, G for Geib, and T-G for tank supplemented by Geib gage.

(3) Under kind of study, dimensions of plot are: (A) 6 by 36.3 feet; (B) 6 by 145.2 feet; (C) 6 by 72.6 feet; (N) 15 by 72.6 feet.

Table 5--Watershed characteristics of Soil Conservation Service Experimental Watersheds, Divisions of Research, Hydrologic Division, North Appalachian Experimental Watershed, near Coshocton, Ohio (compilation of March 1939)

| Item No. | Drainage-area | Gaging-station number | Area above gaging-station, acres | No. rain-gages |  | Dominant soil-texture | Average slope per cent | Land-use (see note 1) |  |  | Ground-water wells |  | Date record started |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  | Re-cording | Stan-dard |  |  | W | G | C | Rec. | Non-Rec. |  |
| 1 | Little Mill Creek, Main Stream | G-91 | 293 | 1 | 4 | Mixed | ..... | w | G | C | 2 | 0 | Nov. 16, 1936 |
| 2 | Little Mill Creek, Main Stream | G-92 | 920 | 3 | 8 | Mixed | ..... | w | G | c | 4 | 0 | Sep. 2, 1936 |
| 3 | Little Mill Creek, Main Stream | G-93 | 1078 | 3 | 10 | Mixed | 14.2 | w | G | c | 6 | 0 | Nov. 1, 1936 |
| 4 | Little Mill Creek, Main Stream | G-94 | 1517 | 3 | 16 | Mixed | ..... | w | G | c | 9 | 0 | Feb. 23, 1937 |
| 5 | Little Mill Creek, Main Stream | G-95 | 2569 | 5 | 32 | Mixed | 16.0 | w | G | c | 15 | 0 | Jan. 1, 1937 |
| 6 | Little Mill Creek, Main Stream | G-96 | 3912 | 8 | 49 | Mixed | ..... | w | G | c | 22 | 0 | Sep. 4, 1936 |
| 7 | Little Mill Creek, Main Stream | G-97 | 4581 | 10 | 58 | Mixed | 16.8 | w | G | c | 27 | 0 | Jan. 12, 1936 |
| 8 | Little Mill Creek, Tributaries | G-5 | 349 | 2 | 6 | Mixed | ..... | w | G | c | 3 | 0 | Mar. 2, 1937 |
| 9 | Little Mill Creek, Tributaries | G-9 | 377 | 2 | 10 | Mixed | ..... | W | G | c | 5 | 0 | Mar. 16, 1937 |
| 10 | Little Mill Creek, Tributaries | G-10 | 122 | 1 | 7 | Mixed | ..... | W | G | c | 1 | 0 | Aug. 18, 1937 |
| 11 | Little Mill Creek, Tributaries | G-11 | 292 | 1 | 8 | Mixed | ..... | W | G | c | 0 | 0 | Mar. 9, 1937 |
| 12 | Little Mill Creek, Tributaries | G-13 | 439 | 5 | 11 | Mixed | ..... | W | g | c | 3 | 0 | Aug. 23, 1937 |
| 13 | Little Mill Creek, Tributaries | G-20 | 373 | 2 | 11 | Mixed | ..... | w | G | c | 6 | 0 | Mar. 11, 1937 |
| 14 | 197 | FS-106 | 1.60 | 1 | 0 | Loam | 15.9 | .. | G | .. | 0 | 0 | Mar. 24, 1939 |
| 15 | 197 | FS-110 | 1.27 | 1 | 0 | Silt-loam | 13.0 | .. | .. | C | 0 | 0 | Mar. 10, 1939 |
| 16 | 197 | FS-118 | 1.84 | 1 | 0 | Silt-loam | 8.7 | .. | .. | C | 0 | 0 | ............ |
| 17 | 197 | FS-124 | 2.11 | 1 | 0 | Silt-loam | 12.3 | .. | G | .. | 0 | 0 | ............ |
| 18 | 197 | FS-128 | 1.84 | 1 | 0 | Mixed | 15.6 | .. | .. | C | 0 | 0 | ............ |
| 19 | 197 | FS-192 | 8.4 | 1 | 0 | Mixed | 13.9 | .. | .. | C | 0 | 0 | ............ |
| 20 | 197 | F-183 | 74.2 | 2 | 1 | Mixed | 14.8 | w | G | c | 2 | 0 | Feb. 17, 1938 |
| 21 | 197 | G-196 | 303 | 9 | 5 | Mixed | 15. | W | g | C | 4 | 0 | Apr. 22, 1937 |
| 22 | X | FS-102 | 1.25 | 1 | 1 | Loam | 18.2 | .. | G | .. | lys | 0 | Mar. 20, 1937 |
| 23 | X | FS-103 | .817 | 1 | 0 | Silt-loam | 11.24 | .. | .. | C | 0 | 0 | Mar. 6, 1939 |
| 24 | X | FS-104 | 1.33 | 1 | 1 | Loam | 20.7 | .. | G | .. | lys | 0 | Mar. 29, 1937 |
| 25 | X | FS-107 | 2.59 | 1 | 0 | Mixed | 15.3 | .. | G | .. | 0 | 0 | July 20, 1938 |
| 26 | X | FS-109 | 1.69 | 1 | 1 | Silt-loam | 12.7 | .. | .. | C | 0 | 0 | July 20, 1938 |
| 27 | X | FS-111 | 1.14 | 1 | 0 | Silt-loam | 8.1 | .. | .. | C | 1 | 0 | ............ |

Table 5--Watershed characteristics of Soil Conservation Service Experimental Watersheds, Divisions of Research, Hydrologic Division, North Appalachian Experimental Watershed, near Coshocton, Ohio (compilation of March 1939)--Concluded

| Item No. | Drainage-area | Gaging-station number | Area above gaging-station, acres | No. rain-gages | | Dominant soil-texture | Average slope per cent | Land-use (see note 1) | | | Ground-water wells | | Date record started |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Re-cording | Stan-dard | | | W | G | C | Rec. | Non-Rec. | |
| 28 | X | FS-113 | 1.62 | 1 | 0 | Silt-loam | 9.9 | .. | .. | C | 1 | 0 | ............. |
| 29 | X | FS-115 | 1.61 | .. | 1 | Mixed | 6.6 | .. | .. | C | 0 | 0 | Dec. 21, 1938 |
| 30 | X | FS-121 | 1.38 | 1 | 0 | Loam | 10.8 | .. | .. | C | 0 | 0 | Mar. 20, 1939 |
| 31 | X | FS-123 | 1.37 | 0 | 1 | Silt-loam | 5.8 | .. | .. | C | lys | 0 | Dec. 3, 1938 |
| 32 | X | FS-129 | 2.47 | 1 | 0 | Silt-loam | 18.6 | .. | G | .. | 0 | 0 | Mar. 26, 1938 |
| 33 | X | FS-130 | 1.63 | 1 | 0 | Mixed | 21.7 | .. | G | .. | 0 | 0 | Apr. 20, 1938 |
| 34 | X | FS-131 | 2.21 | 0 | 23 | Mixed | 21.6 | W | .. | .. | 0 | 0 | Apr. 30, 1938 |
| 35 | X | FS-134 | 0.92 | 1 | 0 | Silt-loam | 23.2 | .. | .. | .. | 0 | 0 | Apr. 30, 1938 |
| 36 | X | FS-135 | 2.69 | 1 | 0 | Silt-loam | 15.3 | .. | G | .. | 0 | 0 | Mar. 27, 1938 |
| 37 | X | FS-185 | 7.00 | 2 | 0 | Mixed | 13.6 | .. | .. | C | 0 | 0 | ............ |
| 38 | X | FS-187 | 7.62 | 2 | 0 | Mixed | 13.8 | .. | .. | C | 0 | 0 | ............ |
| 39 | X | FS-188 | 1.90 | 1 | 0 | Mixed | 9.7 | .. | .. | C | 0 | 0 | ............ |
| 40 | X | FS-191 | 1.04 | 1 | 0 | Mixed | 9.9 | .. | .. | C | 0 | 0 | ............ |
| 41 | X | F-169 | 29.0 | 1 | 1 | Mixed | 15.7 | w | G | C | 0 | 0 | ............ |
| 42 | X | F-172 | 43.6 | 2 | 1 | Mixed | 22.8 | W | .. | .. | 2 | 0 | Jan. 30, 1939 |
| 43 | X | F-177 | 75.6 | 4 | 1 | Mixed | 15.7 | w | G | c | 0 | 0 | ............ |
| 44 | Mill Creek, Main Stream | 297 | 6800 | 6 | 12 | | | | | | 0 | 0 | June 21, 1938 |
| 45 | Mill Creek, Main Stream | 993 | 11820 | 10 | 0 | | | | | | 0 | 0 | ............ |
| 46 | Mill Creek, Main Stream | 994 | 17540 | 12 | 0 | Surveys to be made in near future | | | | | 27 | 0 | Oct. 27, 1936 |
| 47 | Mill Creek, Main Stream | 995 | 22900 | 13 | 0 | | | | | | 27 | 0 | ............ |
| 48 | Mill Creek, Main Stream | 997 | 31340 | 15 | 0 | | | | | | 29 | 0 | Dec. 29, 1938 |
| 49 | Mill Creek, Turkey Run | 497 | 3520 | 4 | 0 | | | | | | 0 | 0 | Oct. 18, 1938 |
| 50 | Mill Creek, Spoon Creek | 697 | 4010 | 6 | 3 | | | | | | 2 | 0 | June 21, 1938 |

Notes: (1) W, G, and C indicate wooded, grassed, or cultivated, respectively; capital letters indicate major use and lower-case letters indicate minor use.

Table 6--Watershed characteristics of Black Lands Experimental Watershed near Waco, Texas

| Item No. | Drainage-area | Gaging-station No. | Area above gaging-station, acres | Date record begun | No. rain-gages | | Average slope, per cent | Land-use (see note 1) | | | Ground-wells | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Re-cording | Stan-dard | | W | G | C | Rec. | Non-Rec. |
| 1 | Brushy Creek, Main Stream | A | 42.0 | May 13,1938 | 1 | 1 | 1.6 | .. | g | C | .. | .. |
| 2 | Brushy Creek, Main Stream | C | 579 | Dec. 11,1937 | 3 | 9 | 2. | .. | g | C | .. | 11 |
| 3 | Brushy Creek, Main Stream | D | 1110 | Nov. 12,1937 | 5 | 21 | 2.1 | .. | g | C | 2 | 25 |
| 4 | Brushy Creek, Main Stream | G | 4380 | Nov. 6,1937 | 21 | 56 | 2. | .. | g | C | 22 | 110 |
| 5 | Brushy Creek, Main Stream | J | 5860 | June 24,1937 | 23 | 79 | 2. | .. | g | C | 25 | 169 |
| 6 | Brushy Creek, Y | Y | 309 | Apr. 22,1937 | 11 | 0 | 2.6 | .. | g | C | 17 | 16 |
| 7 | Brushy Creek, Y | $Y_2$ | 133 | Oct. 4,1938 | 5 | 0 | 2.6 | .. | g | C | 6 | 3 |
| 8 | Brushy Creek, Y | $Y_4$ | 80.9 | Oct. 5,1938 | 4 | 0 | 2.7 | .. | g | C | 3 | 1 |
| 9 | Brushy Creek, Y | $Y_6$ | 20.2 | Sep. 16,1938 | 1 | 0 | 3.2 | .. | .. | C | 3 | .. |
| 10 | Brushy Creek, Y | $Y_7$ | 40.0 | Dec. 16,1938 | 2 | 0 | 1.9 | .. | .. | C | .. | 1 |
| 11 | Brushy Creek, Y | $Y_8$ | 22.3 | Mar. 2,1939 | 1 | 0 | 2.1 | .. | .. | C | 3 | 1 |
| 12 | Brushy Creek, Y | $Y_{10}$ | 21.3 | July 12,1938 | 1 | 0 | 2.3 | .. | .. | C | .. | 1 |
| 13 | Brushy Creek, Z | Z | 310 | ............ | 2 | 8 | ... | .. | .. | C | 1 | 19 |
| 14 | W | $W(W_1+W_2)$ | 306 | June 23,1937 | 13 | 0 | 2.2 | .. | g | C | 5 | 19 |
| 15 | W | $W_1$ | 176 | June 22,1937 | 9 | 0 | 2.1 | .. | g | C | 4 | 9 |
| 16 | W | $W_2$ | 130 | June 23,1937 | 6 | 0 | 2.4 | .. | g | C | 1 | 10 |
| 17 | W | $W_6$ | 42.3 | ............ | 2 | 0 | 2.0 | .. | g | C | .. | 3 |
| 18 | W | $W_8$ | 40.4 | July 11,1938 | 2 | 0 | 2.4 | .. | g | C | .. | 3 |
| 19 | W | $W_{10}$ | 19.7 | July 12,1938 | 1 | 0 | 1.8 | .. | .. | C | .. | 1 |
| 20 | $W_4$ | SW2 | 2.7 | Apr. 1,1938 | 1 | 0 | 1.9 | .. | .. | C | .. | .. |
| 21 | $W_6$ | SW3 | 3.09 | Dec. 7,1938 | 1 | 0 | 1.9 | .. | .. | C | .. | .. |
| 22 | $W_1$ | SW5 | 3.09 | Oct. 1,1938 | 1 | 0 | 3.3 | .. | .. | C | .. | .. |
| 23 | X | SW6 | 3.04 | Nov. 5,1938 | 1 | 0 | 3.3 | .. | .. | C | .. | .. |
| 24 | Y | SW7 | 3.15 | Mar. 9,1938 | 1 | 0 | 1.67 | .. | .. | C | 1 | .. |
| 25 | $W_1$ | SW11 | 3.23 | Mar. 2,1938 | 1 | 0 | 0.94 | .. | .. | C | .. | .. |
| 26 | X | SW12 | 2.97 | Dec. 12,1937 | 1 | 0 | 3.8 | .. | G | .. | | |
| 27 | Y | SW13 | 3.19 | Mar. 8,1938 | 1 | 0 | 2.9 | .. | .. | C | .. | .. |
| 28 | X | SW14 | 3.02 | Mar. 9,1939 | 1 | 0 | 1-3 | .. | .. | C | .. | .. |
| 29 | X | SW16 | 3.17 | Sep. 24,1937 | 1 | 0 | 2.2 | .. | .. | C | .. | .. |
| 30 | $W_1$ | SW17 | 2.99 | Feb. 6,1939 | 1 | 0 | 1.8 | .. | .. | C | .. | .. |
| 31 | $W_1$ | SW18 | 3.04 | Apr. 2,1938 | 1 | 0 | 1.1 | .. | .. | C | .. | .. |
| 32 | W | 1 | .243 | June 8,1938 | 1 | 0 | 2.8 | .. | .. | C | .. | .. |
| 33 | W | 2 | .243 | June 7,1938 | 1 | 0 | 3.0 | .. | .. | C | .. | .. |
| 34 | W | 3 | .243 | June 7,1938 | 1 | 0 | 3.0 | .. | .. | C | .. | .. |
| 35 | W | 4 | .243 | June 7,1938 | 1 | 0 | 3.0 | .. | .. | C | .. | .. |

Notes: (1) Dominant soil-texture is clay.

(2) W, G, and C indicate wooded, grassed, or cultivated, respectively; capital letters indicate major use and lower-case letters indicate minor use.

(3) X and W are watersheds outside Brushy Creek.

Ten recording rain-gages have been installed on the 64 square miles of drainage-area above the control. The data being gathered as a basis for several lines of research will permit the maintenance of a continuous record of the precipitation on the watershed and the discharge at the control with its load of sediment, separated as to suspended load and bed-load.

The systematic recording of data was begun on January 1, 1939. During the entire month of January low-water prevailed which carried very little suspended load and no bed-load. In February several minor floods occurred. The resulting curves were very interesting and somewhat surprising, but are based on such meager data that a statement of what they might indicate is not justified. During the month, the discharge reached a peak of 1200 second-feet, which corresponded to a stage of 2.7 feet as against a maximum stage of about 11 feet, for which measurements will be possible.

Table 7--Watershed characteristics of Central Great Plains Experimental Watershed, Hastings, Nebraska (compiled May 15, 1939)

| Item No. | Drainage | Gaging-station No. | Date record begun | Area above gaging-station, acres | No. rain-gages |  | Average slope per cent | Land-use |  |  |
|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  | Recording | Standard |  | W | G | C |
| 1 | Beaver Creek | 3 | July 16, 1938 | 481 | 2 | 5 | 5 | .. | g | C |
| 2 | Beaver Creek | 8 | July 27, 1938 | 2086 | 4 | 15 | 4 | .. | g | C |
| 3 | Beaver Creek | 11 | July 27, 1938 | 3490 | 6 | 26 | 4 | .. | g | C |
| 4 | Beaver Creek | 1-H | Mar. 27, 1939 | 3.62 | 1 | 1 | 5.6 | .. | G | .. |
| 5 | Beaver Creek | 2-H | Mar. 27, 1939 | 3.40 | 1 | 1 | 7.7 | .. | G | .. |
| 6 | Beaver Creek | 3-H | Mar. 27, 1939 | 3.95 | 1 | 1 | 5.6 | .. | .. | C |
| 7 | Beaver Creek | 4-H | Apr. 20, 1939 | 3.84 | 1 | 0 | 5.4 | .. | .. | C |
| 8 | Beaver Creek | 5-H | Apr. 20, 1939 | 3.93 | 1 | 0 | 5.1 | .. | .. | C |
| 9 | Beaver Creek | 6-H | Apr. 20, 1939 | 4.16 | 1 | 0 | 5.0 | .. | .. | C |
| 10 | Beaver Creek | 7-H | Apr. 20, 1939 | 4.15 | 1 | 1 | 5.1 | .. | .. | C |
| 11 | Beaver Creek | 8-H | Mar. 27, 1939 | 3.93 | 1 | 0 | 4.0 | .. | .. | C |
| 12 | Beaver Creek | 9-H | Apr. 20, 1939 | 3.78 | 1 | 0 | 5.1 | .. | .. | C |
| 13 | Beaver Creek | 10-H | Apr. 20, 1939 | 3.98 | 1 | 0 | 4.8 | .. | .. | C |
| 14 | Beaver Creek | 11-H | Apr. 20, 1939 | 3.85 | 1 | 0 | 4.4 | .. | .. | C |
| 15 | Beaver Creek | 12-H | Apr. 20, 1939 | 3.66 | 1 | 0 | 5.2 | .. | .. | C |
| 16 | Beaver Creek | 13-H | Apr. 20, 1939 | 3.41 | 1 | 0 | 2.5 | .. | .. | C |
| 17 | Beaver Creek | 14-H | Apr. 20, 1939 | 3.35 | 1 | 0 | 3.0 | .. | .. | C |
| 18 | Beaver Creek | 15-H | Apr. 20, 1939 | 3.62 | 1 | 0 | 3.0 | .. | .. | C |
| 19 | Beaver Creek | 16-H | Apr. 15, 1939 | 3.57 | 1 | 0 | 2.5 | .. | .. | C |
| 20 | Beaver Creek | 17-H | Apr. 15, 1939 | 3.96 | 1 | 0 | 4.3 | .. | .. | C |

Notes: (1) All soil-texture is silt-loam.

(2) There are no ground-water wells; no silt-measuring devices.

(3) Stations 3, 8, and 11 are equipped with V-notch weirs, 30-inch crest, 3 to 1 slope, current-meter and laboratory rating; others are equipped with three-foot depth.

(4) W, G, and C indicate wooded, grassed, or cultivated, respectively; capital letters indicate major use and lower-case letters indicate minor use.

Table 8--Small watersheds for runoff-measurements on the demonstration-projects of the Soil Conservation Service, location and characteristics of drainage-areas

| No. | State | Town | No. of areas | Area in acres at runoff-stations | | | | | | Number rainfall-stations | | Dominant soil-texture (see note 2) | Average slope, per cent | Land-use (see note 1) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 1 | 2 | 3 | 4 | 5 | 6 | Rec. | Non-rec. | | | W | O | G | C |
| Stations with at least one season's data | | | | | | | | | | | | | | | | | |
| 1-4 | New York | Bath | 4 | 2100 | 13.8 | 24.2 | 71.7 | .... | .... | 16 | 16 | gr, si lo | 10-20 | w | .. | g | C |
| 4-8 | New Jersey | Freehold | 4 | 21.0 | 36.3 | 50 | 90 | .... | .... | 7 | 7 | lo, sa lo | 4-5 | w | .. | .. | C |
| 8-9 | Maryland | Hagerstown | 2 | 43 | .... | 51 | .... | .... | .... | 4 | 4 | gr, si lo | 8-10 | w | 0 | g | C |
| 10-13 | Georgia | Americus | 4 | 24 | 35 | 30 | 52 | .... | .... | 6 | 6 | sa lo | 2-5 | w | .. | g | C |
| 14-16 | Virginia | Danville | 3 | 12.6 | 27 | 13 | .... | .... | .... | 3 | 3 | sa lo | 5-7 | .. | .. | g | C |
| 17-19 | Ohio | Hamilton | 3 | .... | 17.6 | 28.6 | 15.6 | .... | .... | 3 | 3 | si lo | 5-10 | .. | .. | G | c |
| 20-23 | Illinois | Edwardsville | 4 | 25 | 50.4 | 13.2 | 282 | .... | .... | 11 | 11 | si lo | 5-15 | w | .. | G | C |
| 24-27 | Wisconsin | Fennimore | 4 | 320 | 21 | 54.3 | 170 | .... | .... | 16 | 16 | si lo | 8-10 | .. | .. | g | C |
| 28-31 | Colorado | Colorado Springs | 4 | 10.6 | 39.7 | 35.4 | 35.6 | .... | .... | 6 | 6 | sa and cl lo | 4-7 | .. | .. | G | c |
| 32-34 | Texas | Vega | 3 | 132 | 98.3 | 20.7 | .... | .... | .... | 6 | 6 | si cl lo | 1-25 | .. | .. | G | c |
| 35 | California | Santa Paula | 1 | .... | .... | .... | .... | .... | 78 | 2 | 2 | si cl lo | 3-25 | .. | .. | .. | C |
| 36-40 | Oregon | Newberg | 4 | 13.5 | 12.7 | 13 | 7 | .... | .... | 4 | 4 | cl lo, lo | 10-30 | w | 0 | .. | .. |
| Stations with less than a season's data | | | | | | | | | | | | | | | | | |
| 41-44 | California | Watsonville | 4 | 14 | 18 | 31 | 18 | .... | .... | 5 | 5 | sa lo | 11-40 | w | 0 | g | .. |
| 45-46 | Idaho | Emmett | 2 | 240 | 70 | .... | .... | .... | .... | 5 | 5 | ro | 20-25 | .. | .. | G | c |
| 47-51 | Arkansas | Bentonville | 5 | 12 | 12 | 17 | 20 | 18 | .... | 5 | 5 | si lo, gr si lo | 3-15 | w | .. | G | c |
| 52-57 | Texas | Garland | 6 | 22 | 94 | 10 | 15 | 14 | 15 | 7 | 7 | cl | 1-3 | .. | .. | g | C |
| 58-60 | Oklahoma | Muskogee | 3 | .... | 60 | 26 | 25 | .... | .... | 5 | 5 | fi sa lo | 5-10 | .. | .. | g | C |
| 61-65 | Arizona | Safford | 5 | 520 | 600 | 380 | 780 | 730 | .... | 15 | 14 | sa lo, st, gr | 5-20 | .. | .. | G | .. |
| 66-68 | Maryland | Hagerstown | 3 | .... | 72 | .... | 5.0 | 4.3 | .... | 4 | 4 | gr lo | 8-10 | w | .. | g | C |
| 69 | Ohio | Hamilton | 1 | 193 | .... | .... | .... | .... | .... | 2 | 2 | si lo | 5-10 | w | .. | g | C |
| 70-73 | California | Santa Paula | 4 | 350 | .... | 90 | 43 | 54 | .... | 10 | 10 | si cl, lo | 3.25 | w | .. | g | C |
| Equipment designed or construction started | | | | | | | | | | | | | | | | | |
| 74-76 | New Mexico | Albuquerque | 3 | 204 | 44 | 186 | .... | .... | .... | 5 | 5 | .............. | .... | .. | .. | G | .. |
| 77-79 | New Mexico | Santa Fe | 3 | 140 | 770 | 62 | .... | .... | .... | 7 | 7 | .............. | .... | w | .. | G | .. |
| 80 | Arkansas | Bentonville | 1 | .... | .... | .... | .... | .... | 12 | 1 | 1 | .............. | 6 | .. | .. | .. | C |
| 81 | Oklahoma | Muskogee | 1 | 14 | .... | .... | .... | .... | .... | 1 | 1 | fi sa lo | 5-10 | .. | .. | G | .. |
| 82 | Arizona | Safford | 1 | .... | .... | .... | .... | .... | 500 | 3 | 3 | gr and sa lo | 12 | .. | .. | G | .. |
| 83-85 | Virginia | Blacksburg | 3 | 60 | 5.6 | 20 | .... | .... | .... | 4 | 4 | si lo | 3-20 | .. | .. | .. | C |
| 86 | Georgia | Athens | 1 | 17 | .... | .... | .... | .... | .... | 1 | 1 | .............. | .... | .. | .. | .. | C |
| 87-91 | Maryland | College Park | 5 | .... | .... | .... | .... | .... | .... | .. | .. | .............. | .... | .. | .. | .. | .. |
| 92-93 | Montana | Miles City | 2 | .... | .... | .... | .... | .... | .... | .. | .. | .............. | .... | .. | .. | .. | .. |

Notes: (1) W, O, G, and C indicate wooded, orcharded, grassed, or cultivated, respectively; capital letters indicate major use and lower-case letters indicate minor use.

(2) Under dominant soil-texture the following abbreviations are used: cl = clay; fi = fine; gr = gravelly; ro = rocky; lo = loam; sa = sandy; si = silt; st = stony.

Table 9--Watersheds on demonstration-projects for runoff-measurements, Soil Conservation Service in cooperation with the United States Geological Survey

| Item No. | Region | Watershed | Area, square miles | Date record begun | No. rain-gages | | Land-use (see note 1) | | | Ground-water wells | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Re-cording | Stan-dard | W | G | C | Rec. | Non-rec. |
| 1 | Iowa-Missouri | East Tarko Creek at Blanchard, Iowa | 200.0 | Apr. 1, 1934 | 8 | 15 | 0.5 | 24 | 70 | .. | 12 |
| 2 | | West Tarkio Creek near Westboro, Missouri | 105.0 | Apr. 1, 1934 | 6 | 6 | 0.3 | 15.5 | 78.4 | 1 | 56 |
| 3 | Wisconsin | Little La Crosse, River, near Leon | 77.1 | Apr. 1, 1934 | 4 | 8 | .... | .... | .... | .. | .. |
| 4 | | Coon Creek at Coon Valley | 77.2 | Apr. 1, 1934 | 10 | 3 | 33 | 22 | 41 | .. | .. |
| 5 | North Carolina | West Fork of Deep River near High Point | 32.1 | Feb. 1, 1934 | 3 | 5 | 50 | 4 | 42 | .. | .. |
| 6 | | Muddy Creek, near Archdale | 16.2 | May 19, 1934 | 2 | 4 | 56 | 8 | 31 | .. | .. |
| 7 | | Uharie River, near Trinity | 11.3 | May 17, 1934 | 2 | 3 | .... | .... | .... | .. | .. |
| 8 | Washington | South Fork, Palouse River above Paradise Creek near Pullman | 81.1 | May 22, 1934 | 3 | 11 | 6 | 9 | 83 | .. | 3 |
| 9 | | Missouri Flat Creek at Pullman | 27.5 | Apr. 10, 1934 | 2 | 4 | 2 | 4 | 89 | 1 | 3 |
| 10 | | Fourmile Creek at Shawnee | 71.9 | Apr. 10, 1934 | 4 | 8 | .... | .... | .... | .. | .. |

Notes: (1) W = wooded; G = grass, meadow, or pasture; C = cultivated; values are in percentage.
(2) Dominant soil-texture is silt-loam for items 1, 2, 3, 4, 8, and 9, and sandy clay-loams for items 5, 6, and 7.
(3) Controls are used at all gaging-stations and stream-loads are determined by point measurements.

Table 10--Watersheds for runoff-measurements, Soil Conservation Service, Sedimentation Division, Divisions of Research Stream-Load Stations

| Stream, tributary to, in State | Area, square miles | Record began | No. rain-gages | | Dominant soil-texture | Land-use, per cent |
|---|---|---|---|---|---|---|
| | | | Re-cording | Stan-dard | | |
| Enoree River; Santee River; South Carolina<br>In northeastern South Carolina about 8 miles east of Greenville | 64.4 | 1937 | 10 | .. | Cecil sandy loam and sandy clay loam | Forest,60<br>Cotton,40 |
| Rocky River; Yadkin River; North Carolina<br>Central, 10 miles northeast of Statesville | 85.2 | (a) | .. | .. | To be surveyed | Forest<br>Cotton |
| Sandy Creek; Alabama River; Alabama<br>East-central, 2 miles south of Dadeville | 98.2 | 1937(b) | | | To be surveyed | Forest<br>Cotton |

Notes: (a) = installation inactive; (b) = recorder in operation; controls are used at all gaging-
ions and stream-loads are determined by point measurements; data subject to revision.

The data of these foregoing tables are released to assist in an appraisal of the extent of runoff-measurements being made by the Soil Conservation Service. The data have been compiled from the best available information in Washington, July 1, 1939. More detailed tables are being developed and prepared for an early release by the Soil Conservation Service.

U. S. Soil Conservation Service,
Washington, D. C.,
July 18, 1939

## APPENDIX A-1--PARTICULARS REGARDING EXPERIMENTAL FORESTS AND WORK-CENTERS FOR HYDROLOGIC RESEARCH

Edward Munns

Gale River Experimental Forest
White Mountain National Forest, Coos County, New Hampshire--Area, 1320 acres; spruce-fir forest; relation of forest-density and composition to depth of soil-freezing and infiltration-capacity

Lawrence Hopkins Memorial Experimental Forest
Berkshire County, Williamstown, Massachusetts--Area, 1600 acres; second-growth northern hardwoods; relation of forest-management practice in young hardwood forests to runoff-characteristics of small watersheds

Chenango Experimental Forest
Chenango County, New York--Area, 1300 acres; abandoned agricultural land, northern hardwood forest and coniferous plantations; changes in stream-flow characteristics on small drainages as related to the development of planted coniferous forests

Bent Creek Experimental Forest
Pisgah National Forest, Buncombe County, North Carolina--Area, 5800 acres; comparison of runoff-characteristics of small watersheds including abandoned land, over-grazed pasture, and forest-cover; interception of rainfall by hardwoods, pines, and mixed pine-hardwood forest; use of vegetation in road-bank stabilization

Coweeta Experimental Forest
Nantahala National Forest, Macon County, North Carolina--Area, 4300 acres; cover, hardwood forest; the relation of forest-management practices to the hydrologic cycle; ground-water well-transects of valleys; methods of stabilizing road-banks; water-utilization by vegetation through studies of soil-moisture and stream and ground-water hydrographs

Copper Basin Experimental Forest
Ducktown, Polk County, Tennessee--Area, 6000 acres denuded by smelter-fumes, surrounded by belts of grass and forest-cover; the relation of cover-conditions to the climatic elements of temperature, precipitation, wind, relative humidity, and soil-temperature; runoff from denuded and seriously eroded soils; watershed-rehabilitation measures and their effect on runoff

Holly Springs Work-Center
Holly Springs National Forest, Marshall County, Mississippi--Runoff- and erosion-plots under forest-grass and different methods of cultivation; use of vegetation and simple structures to control gullies on abandoned land; effect of clearing on runoff from previously forested watersheds; effect of forest-management practices on stream-flow; plot-studies on infiltration- and soil-moisture

Irons Fork Experimental Forest
Ouachita National Forest, Polk County, Arkansas--Area, 9000 acres; shortleaf-pine and hardwood cover; plot-studies of runoff and erosion from forest and pasture-land; relation of forest-management practices to flood-flows and peak-discharges; design of small structures to retard stream-flow

La Crosse Work-Center
La Crosse, La Crosse County, Wisconsin--Cooperation with Wisconsin Agricultural Experiment-Station and the Soil Conservation Service; relation of hardwood forest, pastured woods, and pasture to runoff-characteristics of small watersheds; lysimeter-studies of infiltration, runoff, percolation, and water-utilization by grass, hardwoods, and pine

Manitou Experimental Area
Pike National Forest, Teller County, Woodland Park, Colorado--Ponderosa-pine and range-land; range-management practices as related to watershed-management and the yield of usable water; lysimeter-studies of infiltration, runoff, and percolation as influenced by grass-cover; runoff and erosion-plot studies under grass-cover; relation of forest-and-range-management practices to runoff from small watersheds

Fraser Experimental Forest

Arapaho National Forest, Grand County, Colorado--Area, 1700 acres; lodgepole pine-cover; forest-management practices as related to watershed-management with particular emphasis on snow-storage, interception, and rate of melting

Priest River Experimental Forest

Kaniksu National Forest, Bonner County, Idaho--Area, 6104 acres; western white-pine, mixed conifer-forest; relation of forest-management practices and methods of cutting to runoff and erosion from small watersheds

Boise Basin Branch Station

Boise National Forest, Boise County, Idaho--Bunchgrass type; relation of range-management practices to watershed-management and yield of usable water; watershed-rehabilitation measures; erosion-control methods on range-land; lysimeter-studies on infiltration, percolation, runoff, and erosion

Davis County Work-Center

Wasatch National Forest, Davis County, Utah--Range and mountain shrub-cover; studies of watershed-rehabilitation, primarily for flood-prevention; relation of range-management to yields of usable water; development of methods of measuring debris-laden flood-flows; snow-storage and rate of melting as affected by forestry

Great Basin Branch Station

Manti National Forest, Sanpete County, Utah--Mountain shrub-grass range-cover; studies of the relation of grazing intensity to runoff and erosion; watershed-management practices to increase yield of usable water from mountain watersheds; snow-accumulation and rate of melting as related to grazing practice

Parker Creek Experimental Forest

Tonto National Forest, Gila County, Arizona--Area, 1800 acres; semi-desert shrub-grass, mountain brush, and ponderosa-pine; relation of range-and-forest-management practices to runoff, infiltration, erosion, and yields of usable water; lysimeter-studies on the effect of grass- and shrub-cover on infiltration, runoff, percolation, erosion, and the utilization of water by vegetation; watershed-rehabilitation measures; road-erosion control

San Dimas Experimental Forest

Angeles National Forest, Los Angeles County, California--Area, 17000 acres; chaparral-cover with small amount of woodland; relation of watershed-management to yield of usable water; plot-studies of erosion and runoff from chaparral with special reference to the effect of forest-fires; road-bank stabilization; channel-stabilization; watershed-rehabilitation measures; lysimeter-studies on relation of chaparral and tree-cover to infiltration, runoff, erosion, percolation, and utilization of water by vegetation

Kings River Work-Center

Sierra National Forest, Fresno County, California--Woodland-grass cover, second-growth ponderosa-pine, fir-pine; relation of timber-and-range-management practices to stream-flow, erosion, and yield of usable water; runoff and erosion plots

Northfork Work-Center

Sierra National Forest, Madera County, California--Ponderosa-pine, mountain-brush; plot-studies of runoff and erosion as influenced by forest-management practices; lysimeter-studies of the relation of brush- and forest-cover to runoff, erosion, infiltration, and percolation

U. S. Forest Service,
Division of Forest Influences,
Washington, D. C.

# REPORT OF THE COMMITTEE ON PHYSICS OF SOIL-MOISTURE, 1938-39

(The validity of the assumption that it is possible to produce
different moisture-percentages in field-soils)

F. J. Veihmeyer, Chairman

[The following members constitute the Committee:
Dr. F. J. Alway, University of Minnesota, University Farm, St. Paul, Minnesota
Dr. L. D. Baver, University of Missouri, Columbia, Missouri
Dr. G. B. Bodman, University of California, Berkeley, California
Dr. T. F. Buehrer, University of Arizona, Tucson, Arizona
Dr. I. A. Denison, National Bureau of Standards, U. S. Department of Commerce, Washington, D. C.
Dr. N. E. Edlefsen, University of California, Davis, California
Dr. H. J. Fraser, California Institute of Technology, Pasadena, California
Dr. R. E. Horton, Voorheesville, New York
Dr. O. W. Israelsen, Utah State Agricultural College, Logan, Utah
Dr. P. G. Nutting, U. S. Geological Survey, Washington, D. C.
Dr. L. B. Olmstead, Bureau of Chemistry and Soils, U. S. Department of Agriculture, Washington, D. C.
Mr. W. O. Smith, Bureau of Chemistry and Soils, U. S. Department of Agriculture, Washington, D. C.
Mr. E. A. Willis, Bureau of Public Roads, U. S. Department of Agriculture, Washington, D. C.
Dr. F. J. Veihmeyer (Chairman), University of California, Davis, California]

The relation between volume of compacted soils and moisture-content recently has come to be used as a criterion of the desirability of use of that soil as an engineering material. Numerous articles have appeared describing the methods used to bring the soil to the desired moisture-content.

It is obvious that any granular material, such as soil-particles, may be wetted to any degree of wetness between saturation and complete dryness if the material can be handled in small batches and can be thoroughly mixed. If the water is applied in the form of a fine spray, the process is facilitated. This is a tedious process requiring constant checking by weighing even with small quantities of soil. As a procedure in the laboratory it is seldom possible to bring the moisture-content to within about one per cent of the desired amount even with quantities of soil as small as one kilogram. When the amount of soil is increased the departure from the actual moisture-content of the prepared sample and the desired condition may be much greater than that indicated. Attempts to wet the soil to a predetermined moisture-content in a borrow-pit, for subsequent removal to the place of use, in many instances may be disappointing. If the soil is mixed as is done on some construction jobs, of course, it is possible to bring the soil approximately to a desired uniform moisture-content.

When water is applied to permeable soils in place in the field it is rather quickly distributed and the soil is raised throughout the portion wetted to a certain moisture-content which is determined principally by the texture of the soil, that is, by the size of the soil-particles. Structure, which refers to the arrangement of the soil-particles, exerts much less influence upon the water-holding capacity of the soil than does texture. But structure has a decided effect upon the rate of infiltration of water into the soil. The moisture-condition of the portion of the soil which is wetted is referred to in a number of ways, among which are: Specific retention; maximum water-holding capacity; normal field-capacity; and maximum field or capillary capacity. The simpler term field-capacity has come into rather general use and it may be defined as the amount of water held in the soil after the excess gravitational water has drained away and after the rate of downward movement of water has materially decreased, which usually takes place within two or three days on permeable soils of fairly uniform structure and texture.

The rapid lowering of the water-content to the field-capacity following the application of water is not strictly true when enough water is applied to saturate the column of soil down to the water-table. In this case drainage is continuous for a long time at a very slow rate so that many days will be required before the field-capacity is reached. The distribution of moisture immediately following the application of water is very rapid under the usual case where the soil is not wetted down to the water-table.

The amount of water required to saturate a given volume of soil, which, of course, is determined by the total pore-space in the soil, does not bear a direct relation to the texture of the soil. It is frequently stated that sands when saturated hold less water than clays. The report of this Committee for the year 1934-35 shows that such a generalization is not justified from the available data. There do not seem to be consistent differences in porosities of soils of the same origin. The porosities of clays may be no greater than those of sands of the same series.

A number of investigators have shown that the field-capacities of fine-textured soils are about the same as the moisture-equivalent; but that sandy soils, those with moisture-equivalents of less than about 14 per cent moisture, sometimes have field-capacities which are higher than their moisture-equivalents. The agreement between the moisture-equivalent and field-capacity, therefore, furnishes a simple laboratory means of determining approximately the amount of water a given soil in the field can hold when free drainage is provided for fine-textured soils.

The question arises whether there is a practical method of wetting soils in place in the field to a moisture-content less than field-capacity or the moisture-equivalent. Agricultural and engineering literature frequently carries statements that this can be done. In the former, experiments are reported in which the soil is said to be maintained at any desired moisture-content, such as 10, 20, 30 per cent, or a theoretical amount such as "optimum," by applying water to the surface. In engineering literature, also, methods are described in which predetermined moisture-contents are said to be produced by application of the water to known quantities of soil. These procedures are based upon the assumption that capillary action will distribute the water throughout the entire mass of soil and the resulting moisture-content will be determined by the amount of water applied, the more water applied the wetter will be the soil. actually, when a certain amount of water is applied to a given volume of soil, that amount of water if less than the amount required to bring all of the soil to field-capacity, wets only a certain depth of soil to its field-capacity and then movement practically ceases. To secure further penetration more water must be applied. The depth of penetration depends upon the kind of soil and its relative dryness before the water was applied. A uniform moisture-content less than the field-capacity is not produced. The soil must be wetted to its field-capacity or not at all. Hence, if after determining the moisture which coincides with the minimum volume of a compacted soil, an attempt is made to produce this moisture-content in a soil in place in the field, unless it also coincides with the field-capacity, the results will not be those anticipated.

Soil is comprised of particles varying tremendously in size and since the field-capacity is so largely determined by texture, it is apparent that great differences will be found in the field-capacity from place to place in the soil. In fact, soils that appear to be uniform in texture have been found to vary as much as 50 per cent in field-capacity even though samples were taken within a radius of a few feet of each other. Consequently this variation in texture must be taken into account in the application of the results of tests in the laboratory on selected samples.

The great variability in the texture of soils in masses, such as those used in engineering construction, and the difficulty of adequately sampling the soil for tests in the laboratory and the improbability, or almost impossibility, of bringing the soil uniformly to the desired moisture-contents raise doubts as to the validity of the statement in engineering literature where claims are made that this has been accomplished.

Likewise, statements in agricultural literature in which it is claimed that predetermined moisture-contents were maintained in soils upon which plants were growing are open to question. In fact, since the soil cannot be mixed it is impossible to produce a uniform moisture-content less than the field-capacity by the application of water.

Comments on the above report were solicited from all members of the Committee. Replies were received from Alway, Baver, Bodman, Buehrer, Denison, Edlefsen, Horton, Israelsen, Olmstead, and Veihmeyer. All of these approved the report and some made suggestions for minor changes which have been incorporated in it. The following comments are submitted as additional contributions to the subject:

L. D. BAVER--I would question the emphasis placed upon the statement that structure exerts much less influence than texture upon the water-holding capacity of soils. This is true if wide enough variations in texture are considered. I do not believe that this statement will hold so closely for soils in the humid region. In general, the point of view is correct, but I believe the report suggests too much emphasis on texture.

T. F. BUEHRER--In my own work on the effect of puddling on the amount of water "bound" by a soil, particularly when subjected to puddling, I have been up against this very difficulty. It has not arisen so much in the case of the puddled soils, since by mechanical working one can secure fairly uniform moisture-distribution, although even in that case, one rarely succeeds in making the sample accurately to a predetermined moisture-content. I have been weighing the puddled sample prior to making the dilatometer-determination, after having weighed a separate sample of it for a moisture-determination as a check.

The chief difficulty has arisen in making up the normal or unpuddled samples to a desired moisture-content. Neither evacuation prior to the addition of the water, nor the alternate addition of small amounts of soil and water, has resulted in uniformity of moisture-distribution. Spraying and mixing, by rolling or otherwise, seem to result in puddling to some extent even when all possible precaution is taken to avoid it. We are still looking for a reliable method of making up an unpuddled soil to a predetermined moisture-content.

N. E. EDLEFSEN--Since field-capacity is a term used to express the moisture-content after rapid drainage has ceased, a change in structure of a given soil might change the field-capacity of that soil. For example, if a soil were highly dispersed, the time for the excess water to drain might be materially lengthened. This, of course, would be of no practical importance in agriculture in altering the amount of water which could be stored in a soil since it would be unlikely that the structure of an appreciable portion of the soil-mass would be altered markedly under any normal cultural practice. In engineering construction, however, it is possible to change the amount of water a soil holds by changing the structure.

College of Agriculture,
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Davis, California

## REPORT OF THE COMMITTEE ON UNDERGROUND WATERS, 1938-39

David G. Thompson, Chairman

In preparing the report of the Committee on Underground Waters of the Section of Hydrology for the final year of the triennium, it becomes evident that the collection of fundamental data relating to the hydrology of underground waters continues at a rate comparable to that maintained in the past few years, and perhaps even at an accelerated rate. Almost every extensive practical investigation of ground-water supplies offers some opportunity for study of fundamental problems, in fact many of them require such fundamental study. With a larger number of investigations in progress, and with fairly liberal appropriations much new and valuable information is being discovered.

Some idea of the increase in ground-water studies since the organization of the Section of Hydrology may be given by a few statistics on the work of the Division of Ground-Water of the Federal Geological Survey, which does the largest amount of ground-water work in the United States. In 1932 the Division worked on about 50 projects in 25 States, in 15 of which and in Hawaii the investigations were made in cooperation with States, or other local Governmental agencies. During the current fiscal year work has been completed, or is in progress, on about 100 investigations in 35 States, Hawaii, and the Virgin Islands. The number of States cooperating on the work has increased to 24. During the current fiscal year about $375,000 will be spent for ground-water investigations by the Federal Geological Survey and cooperating organizations, as compared to about $175,000 spent during the fiscal year ended June 30, 1932.

A significant fact is the increasingly large amount of money that is being spent for drilling of test-holes and for making pumping tests or other experimental tests as part of the cooperative investigations. During the past two or three years from a few hundred to as much as $20,000 has been spent for test-drilling and other large-scale field-tests in each of ten studies by the Federal Geological Survey and organizations cooperating with it. The large expenditures for this work are a recognition not merely of the value of our ground-water supplies, but also of the need for more accurate basic data, and of the fact that with such basic data the ground-water hydrologist can reach reasonably reliable conclusions.

There has also been a great increase in facilities for observations of fluctuations of ground-water level and artesian head. In the report of your Chairman for 1933--the first to contain numerical data on this subject--it was estimated that the Geological Survey was making more or less periodic measurements on about 2500 wells and that about 115 water-stage recorders were installed on wells to obtain continuous records of the fluctuations of water-level. It was estimated that two and a half years earlier only about 50 recorders were in use. In 1937 there was issued the first annual report giving data on the water-level in many wells during 1936 and for many wells the data covered earlier years. The fourth annual report, for 1938, now in preparation, will contain records of about 5000 wells in 28 States and in the Territory of Hawaii. More than 200 water-stage recorders are now installed on wells. In addition to the wells observed by the Federal Geological Survey many wells are being measured by other Federal and State agencies. The Soil-Conservation Service has 135 observation-wells of which about 60 are equipped with water-stage recorders. The records of some of these wells have recently been published in graphic form [see 1 of "References" at end of paper]. A large but undetermined number of wells are measured in investigations of the Bureau of Agricultural Engineering, the Bureau of Agricultural Economics, Bureau of Plant Industry, the Forest Service, the National Park Service, and the Bureau of Reclamation. In southern California State, county, and other non-Federal agencies are measuring some 2000 wells. It is probable that the total number of wells now being measured more or less regularly exceeds 10,000.

Memory recalls now but faintly that only five years ago, in 1934, large areas of the country were visited by severe drought, and there was a revival of a discussion, begun almost 40 years earlier, as to whether there was a continual downward trend of ground-water levels. The observations since then have shown that in large parts of the areas affected by drought the water-levels have risen, although there has been no excessive precipitation. In some restricted localities where the precipitation has continued to be deficient, the water-level has declined farther, and new low levels were reported in some places. The water-level has also declined in some areas of heavy pumping.

In certain localities the rise in water-level resulting from heavy rains has been striking. For example, R. M. Leggette, in charge of ground-water studies on Long Island by the Federal Geological Survey, reports as follows: "During the last half of September, 1938, Long Island, New York, and adjacent New England experienced one of the most severe hurricanes on record. On Long Island about ten inches of rain fell during the period September 17-21. A study of the ground-water recharge resulting from this storm is being made by the Jamaica office of the United States Geological Survey. Records of ground-water levels in numerous observation-wells on Long Island and detailed stream-flow records for a number of streams on the Island are available for the year 1938. A study of the records indicates that a very large percentage of the rain that fell during this storm penetrated into the ground and produced ground-water recharge."

As a result of the hurricane in September and other recent heavy storms in parts of Nassau and Suffolk counties, on Long Island, ground-water levels in April, 1939, were as high as, or higher than, at any time since more or less regular observations were begun in 1903. Lake Ronkonkoma, in western Suffolk County, is essentially a huge open well about a mile in diameter, the level of which reflects closely the ground-water level in the territory surrounding it. In April, 1939, the level of the Lake was within two feet of the previous observed highest level, which was reached in 1891 [2]. Inasmuch as general observations go back for 60 or 70 years prior to 1891, the present high level is almost as high as it has been at any time in more than 100 years. The high ground-water level, especially in Nassau County, is all the more striking in view of the fact that, since 1904, an average of about 50 million gallons a day has been pumped from wells in the County for public supply, plus an undetermined quantity for industrial and domestic use.

Phenomenal rises have been reported from some localities in southern California as a result of heavy precipitation. According to a very detailed record of a well (the Williams Well) near the stream-channel of Santa Ana River in San Bernardino County, furnished to the United States Geological Survey by the Gage Canal Company, which goes back to 1892, the lowest water-level, 59.48 feet below the measuring point was reached in October, 1936 [3]. Following heavy rains in the winter of 1936-37 the water-level in this Well rose on May 1, 1937, to a level only 14.50 feet below the measuring point; and, after a seasonal drop of about 20 feet, it rose further to a level only 6.92 feet below the measuring point on April 23, 1938 [4]. In another well, known as the Baldwin Park Well, and a companion well, for which the record goes back to 1903 [3], the water-level reached an all time low of 257.60 feet above sea-level in October, 1934, and thereafter rose gradually with seasonal fluctuation. As a result of heavy rains in the winter of 1936-37, it rose very rapidly from a level 266.98 feet above sea-level on December 15, 1936, to 302.44 feet above sea-level on June 14, 1937, or 35.46 feet. With seasonal fluctuations it rose further to a level 309.99 feet above sea-level on May 5, 1938, or higher than it had been at any time since March or April, 1923. Roughly comparable rises have been reported from other wells.

Harry F. Blaney reports that the Bureau of Agricultural Engineering in cooperation with the Bureau of Plant Industry and the Department of the Interior, has continued observations on ground-water conditions in the Bard-Yuma Area along the California side of the Colorado River. Additional observation-wells were installed during 1938. Readings are now taken once a month at 181 points which include water-levels in wells, drains, canals, a lake, and the Colorado River. Early in 1939 some water was diverted into the All-American Canal by the Bureau of Reclamation. During this period observations were made more frequently so as to determine the effect of seepage-losses from the Canal on ground-water levels in different localities.

Mr. Blaney also reports that during 1938 the Division of Irrigation, of the United States Bureau of Agricultural Engineering, and the California State Division of Water-Resources started cooperative hydrologic investigations in San Luis Rey Valley, San Diego County. These include ground-water studies to determine water-table fluctuations, capacity of underground reservoirs, feasibility of water-spreading, safe pumping-yield, and salt-water intrusion.

Some of the most interesting current studies have produced and are producing information in regard to the compressibility and elasticity of water-bearing formations. Some 15 years ago tidal effects in wells near the coast at Atlantic City were observed which could only be explained as a phenomenon of compressibility and elasticity [5]; and since then similar observations have been made in a number of places near the ocean. During the past year, for the first time in this country, fluctuations of water-level were found in wells several hundred miles inland from the ocean, which are attributed to earth-tides. They were first recognized in a well in New Mexico, but recently have also been observed in a well in Iowa. The records obtained in both States are described in a paper by T. W. Robinson presented at the 1939 meeting of the Section of Hydrology and published in these Transactions [pp. 656-666].

Fluctuations due to changes in pressure caused by the passage of railroad-trains--another manifestation of the compressibility and elasticity--are described in a paper by C. E. Jacob in these Transactions [pp. 666-674].

Twice in reports of the Committee on Underground Waters--in 1934 and 1937--reference has been made to sinking of the land in Santa Clara Valley, as revealed by releveling by the United States Coast and Geodetic Survey. In this connection, the following quotation from a letter from J. H. Hawley, Acting Director of the Coast and Geodetic Survey, in response to an inquiry from O. E. Meinzer, as to the results of more recent leveling in Santa Clara Valley, is of interest:

"As you may know, the Coast and Geodetic Survey has run and rerun a series of level-lines in the vicinity of San Jose, California, since 1932. The maximum settlement found is about five feet. The greater amount of this settlement had taken place prior to the first rerunning of the lines in 1932, but subsequent rerunnings have indicated additional settlement until the last year or two, when the settlement has been slowed up considerably.

"The last releveling was completed recently and as yet the work is only in preliminary form. However, the field-work was of such scope that I do not believe any large changes will be found, and I quote from a letter of March 9, 1939, received from the Chief of Party who was in charge of the work: 'The results of the most recent leveling in this vicinity have proved very interesting. A rising of the valley-floor is now indicated instead of settlement. Over a period of a little less than four months, the field-elevations indicate a maximum average rise of three cm.'

"This information is preliminary and is subject to change when the adjustments are made. The letter also states that it is understood the artesian water-pressure in the Valley shows the greatest increase in the vicinity where the levels indicate the greatest rise. The conditions indicate that the ground-water is recovering from the big drop of the last 15 years."

There is an unusual opportunity to observe the compressibility and elasticity of water-bearing strata at the Conchas Dam in New Mexico, as described in the following statement by Dr. C. V. Theis, of the Federal Geological Survey, who is participating in the investigation. "Due to the interest of the Corps of Engineers and especially of Captain Hans Kramer, District Engineer, Conchas District, in charge of the construction of Conchas Dam on the Canadian River in New Mexico, an investigation that promises to be very fruitful of basic information regarding the compressibility of artesian aquifers, is in progress. The main section of the Dam is a concrete gravity-structure, placed in separately movable monoliths about 200 feet high. The main section of the Dam is founded on an artesian sandstone extending about 40 feet below the base of the Dam, which in turn rests upon about 30 feet of dense shale lying upon artesian sandstone in excess of 100 feet thick [5]. The monoliths of the Dam, now nearing completion, have settled a maximum distance of a little over two inches. The settlement was expected and differential movement of the monoliths was provided for in the design. The unusual feature of the process of settlement was that certain of the monoliths, while under construction, temporarily rose a maximum of about one inch. This rise was observed during the period of recovery of artesian head after the unwatering of the foundation when the foundation-courses of concrete were poured, and immediately following an extended period of high-pressure grouting at the heel of the monoliths that rose. The areal distribution of the rise in this section of the Dam appears to conform very closely to the distribution of the increased hydrostatic pressure caused by the grouting and the recovery after pumping. The action of the Dam appears to give a striking confirmation of Meinzer's theory of the elasticity of artesian aquifers and the phenomena observed were recognized and described as consequences of this process by the local officials in charge.

"Of great interest is the fact that determinations of the moduli of elasticity of specimens of the artesian sandstone made in the laboratory make it very improbable that expansion and compression of the sandstone itself under the known changes in hydrostatic head could account for the rise and fall observed. Accordingly the characteristics of the underlying shale are being carefully studied. Preliminary tests of specimens of this shale in the laboratory have indicated that it is possible to expand and contract it by increasing and decreasing the hydrostatic pressure imposed on it without changing the externally applied load. The change in volume under change in hydrostatic pressure was much larger than can be expected in a normal sandstone. The data available at present indicate that the elasticity of this artesian sandstone is due to the included shaly beds.

"Equipment being installed to study in detail the settlement of the foundation includes plumb-bobs permanently hung inside the Dam, optical tilt-meters, underground bench-marks that will measure the compression of the shale and the overlying sandstone, and hydrostatic pressure-wells set inside the underlying shale to measure changes in hydrostatic pressure within the shale. Accurate surveys will also be made periodically to determine change in elevation of bench-marks in each monolith and to determine the deflection of the face of the Dam. As the foundation-loads at the heel and toe of the Dam will change with changing reservoir-level, it is expected that there will eventually be obtained a very instructive and detailed record of the effects of loading an artesian aquifer. A. K. Sibley, First Lieutenant, Corps of Engineers, has largely been responsible for the design and installation of the equipment and procedure for the investigation.

"In connection with the study, the fluctuations of water-level in an observation-well caused by barometric changes and changes in the rate of pumping in nearby wells are being studied for possible correlation with the modulus of elasticity of the sandstone determined from laboratory tests."

The opportunity to obtain at the Conchas Dam observations of considerable scientific interest, as well as of practical value, is one that is not often presented; and it is to be hoped that funds may be available to carry out these observations to the fullest extent.

Brief mention may be made of another set of observations bearing on the phenomena of compressibility and elasticity, namely, the fluctuations of artesian pressure in a water-bearing formation underlying a small area in Ogden Valley, Utah, that has been flooded by the recently filled Pine View Reservoir. As the level of the Reservoir rose about 55 feet, the pressure in an artesian well outside the flooded area increased about 15 feet, at least some of the increase being attributed to the added load of the water in the Reservoir [7].

In a paper presented at the general scientific session of the American Geophysical Union in 1933, in discussing the subject of compressibility and elasticity, O. E. Meinzer stated that automatic water-stage recorders were becoming the principal instruments of precision in ground-water hydrology [8]. In another paper presented at the meeting of the Section of Hydrology in Washington in April, 1937, he pointed out that, in spite of the fact that the term "geophysics" is by popular usage generally understood to refer to certain special methods of investigating the physics of the Earth, such as electrical-resistivity methods, seismologic methods, torsion-balance methods, etc., many other methods of investigation, some involving the use of much simpler apparatus, such as automatic water-stage recorders, pressure-gages, current-meters, etc., are just as much to be considered as phases of the science of geophysics. He stated [8]: "It may be predicted that water-stage recorders will eventually come to have greater value in the study of physics of the Earth, exclusive of hydrology, than is now understood, especially in studying the elastic properties of the rock-formations." The investigations of phenomena involving the compressibility and elasticity of water-bearing formations which have just been cited show that this prediction is already being fulfilled, and suggest some possiblities for future study.

Another instance in which water-level recorders are proving useful in the study of geophysical phenomena relates to fluctuations of the water-level in wells produced by earthquakes. These studies have been under investigation for several years and have made a contribution to the science of seismology. Recently H. E. Thomas, of the United States Geological Survey, has made a study of the effects of earthquakes in Alaska and Chile upon the water-levels in wells in Utah and in other States. This study is producing some significant results.

Considerable investigational work is being done on contamination of fresh-water-bearing strata by salt water--either from the ocean, from salt-connate water in strata associated with fresh-water-bearing strata in inland areas, or from brines pumped in oil-fields.

A study of the variations in chloride-content of the ground-water in the western part of Long Island resulting from salt-water encroachment is being continued by M. L. Brashears of the United States Geological Survey.

H. C. Barksdale, in charge of ground-water investigations in New Jersey by the Federal Geological Survey in cooperation with the State Water-Policy Commission, reports that the encroachment of salt water into sands that originally yielded fresh water is being observed by means of a group of test-wells and monthly samples in the Atlantic City and Parlin areas. In both areas the fresh-water head had been lowered materially by heavy pumping before the advance of salt water was discovered and in both the rate of pumping has been materially reduced since its discovery in an endeavor to delay the contamination as much as possible. At Atlantic City the rate of pumping from the 100-foot sand affected has been reduced to about one-fourth of its former value for several years. The results of the sampling program have shown some shifting of the position of the salt water, but have produced no conclusive evidence that a renewal of the fresh-water head may ultimately freshen the sand after it has been contaminated with salt water by over-pumping. Actually it seems probable that, while the intake of salt water may have been reduced or stopped altogether by the increased fresh-water head, the salt water already in the sand is continuing to advance slowly toward the wells that are still being pumped. At Parlin, near Perth Amboy, the situation was aggravated by the dredging of a barge-canal across a part of the water-bearing sand that had previously been protected by a layer of relatively impervious mud. A ready means of access was thus provided for the salt water, as soon as the fresh-water head was lowered enough to permit it, to enter the sand. Records in this area indicate that water containing 300 parts per million of chloride has advanced about two miles in six years. They also show that the salt water advancing through the sand past any given point does not increase steadily in its chloride-content but appears to increase in waves of higher and lower salinity. This is probably because of seasonal changes in the salinity of the water in the tidal estuaries where the salt water entered the sand and to fluctuations in the fresh-water head in the intake-area caused by changes in the rate of pumping from time to time.

In Kansas, in an investigation by the United States Geological Survey in cooperation with the Kansas Geological Survey and the Kansas State Board of Health, many test-wells have been drilled to determine the direction and rate of movement of salt water seeping from brine-storage ponds--so-called evaporation-ponds. The following statement in regard to these studies has been furnished by S. W. Lohman, of the Federal Geological Survey.

"Studies were made to determine the vertical and horizontal movements of oil-field brines after their introduction into fresh-water-bearing sands and gravels by downward percolation from so-called evaporation-ponds. In one oil-field, numerous driven wells were put down at points down the hydraulic gradient from evaporation-ponds. Samples of water were taken from the water-bearing beds at vertical intervals of about two feet. The chloride-content of each sample was determined in a portable field-laboratory. It was found that owing to the higher specific gravity of the brine, it sank rapidly downward and somewhat laterally through the fresh-water sands, without appreciable dilution. The downward movement was arrested by the first impervious bed encountered, causing the brine to spread laterally as a thin layer along the bottom of the more permeable bed.

"Studies also have been started near the City of Winfield, Kansas, to determine the extent to which the City well-field has been contaminated by oil-field brines and what steps should be taken to remedy the trouble. About 40 driven wells were put down on a 160-acre tract to determine the vertical and horizontal distribution of chloride and to furnish data for a water-table contour-map. Periodic sampling of the 40 driven wells will furnish data for a series of isochlar maps showing the progress being made."

The disposal of brines from oil-fields in a way to not contaminate fresh ground-waters or surface-waters involves many problems of a chemical, hydrological, and geological nature, and the cost of proper disposal will be considerable. In a recently issued report of the National Resources Committee [9] on "Water-pollution in the United States," it is stated that the capital investment required for treating and disposing of oil-field brines is conservatively estimated as at least $100,000,000, and it is conceivable that the ultimate cost might be double this figure. It is further indicated that annual operating costs would be high--perhaps as much as 18 to 33 per cent of the capital investment. The problems involved have been under study for some time. The United States Bureau of Mines has recently published data in regard to seven systems for treating brine for disposal into wells in Kansas oil-fields, with a consideration of chemical and mechanical problems [10]. Another paper published during the year describes several brine-disposal systems in oil-fields in Oklahoma that have been constructed at an aggregate cost of $1,300,000 [11].

An intensive study of the movement of salt and fresh water in a small area in the vicinity of Carlsbad, New Mexico, has been under way for about two years and is being continued. The problem is the determination of the sources of the salt influx into the Pecos River in this vicinity. It is complicated by the facts that on the one hand beds of rock-salt underlie the area at comparatively shallow depth and are reached by the ordinary ground-water of the area, and that, on the other hand, a surface-depression that has always contained a lake of concentrated brine has been used for the disposal of waste brine resulting from potash-refining. The study should eventually yield valuable information regarding the effects of solution in gypsiferous and saline beds, and on the relative movements of salt and fresh water underground. A first report on the area has been prepared by T. W. Robinson and W. B. Lang of the United States Geological Survey and will be published in the forthcoming 12th and 13th Biennial Report of the State Engineer of New Mexico.

Information in regard to salt-water problems being investigated in Texas is given in a statement later in regard to investigations in progress in that State.

In addition to the problems of salt-water contamination, instructive studies of the geochemical relations of ground-waters in parts of the Atlantic and Coastal plains have been made by Margaret Foster of the United States Geological Survey. A paper on the "Geochemical relations of the ground-waters of the Houston-Galveston Area, Texas," was presented by Miss Foster at the meeting of Section E, of the American Association for the Advancement of Science, in Richmond, Virginia, December 27, 1938, and at the meeting of the Geological Society of Washington, March 8, 1939. In this paper, which summarizes the results of a detailed study of the ground-waters of the Area, it is shown that: (1) The primary action of waters entering the surface-materials is solution of calcium carbonate; (2) the shallow waters in the different formations differ characteristically in their content of calcium bicarbonate and in their total mineral content; (3) these differences may be correlated directly with the soluble mineral content of the rock-materials of the different formations; (4) there is a gradual alteration with depth in the chemical character of the waters in the different formations, changing from calcium bicarbonate to sodium bicarbonate, due to a secondary reaction between the ground-waters and base-exchange minerals in the rock-materials; (5) calcium-chloride waters found in the vicinity of some of the salt-domes may be attributed to a reverse of this softening process; and (6) disturbance of the strata is indicated by the chemical character of some of the waters in the vicinity of Blue Ridge and Pierce Junction domes. Similar studies are being made in other parts of the Coastal Plain and further investigations are in progress on the interpretation of the chemical character of the ground-waters.

F. H. Lahee reports that several oil-companies have in progress investigations to determine how water moves into sands which contain oil as the oil is withdrawn.

Among investigations of other phases of ground-water hydrology, the following may be mentioned: During March, 1939, an exceptional opportunity was offered for conducting a field pumping-test in a group of artesian wells on the south shore of Long Island. Two deep test-wells are being drilled for the City of New York in a location where bed-rock lies about 1200 feet beneath the surface, and the Lloyd sand--one of the important artesian aquifers on Long Island--lies about 800 feet beneath the surface. Prolonged pumping tests will be made of each water-bearing horizon encountered in the Lloyd sand. Fortunately, there are five unused 800-foot wells in the vicinity of the test-wells that are being drilled. The entire layout offers an unusual opportunity for conducting a field pumping-test on a deep artesian aquifer. It has been necessary to equip each of the observation-wells with an automatic water-stage recorder, for the wells are all located so near the ocean that the water-level in them fluctuates about four feet with the tide. The instrumental records being obtained have an extended time-scale to permit more detailed study of the pumping tests. Tide-gages have also been installed in the Ocean and Jamaica Bay nearby, so that the time-relations will be apparent. This study, in charge of R. M. Leggette, is a part of ground-water studies on Long Island by the United States Geological Survey in cooperation with the New York Water-Power and Control Commission, and Nassau and Suffolk counties, and informally with the City of New York. Also, as a part of the Long Island investigations, the study of variations in ground-water temperature as affected by the return of large quantities of warm water to the ground from air-conditioning installations, reported on by M. L. Brashears in the Transactions for 1937, is being continued.

Dr. Willard Gardner has brought to the attention of the Committee investigations by Dr. Don Kirkham, of the Department of Physics at Utah State Agricultural College, in regard to flow of water through a homogeneous soil. A paper on the subject by Dr. Kirkham was read by title at the annual meeting of the Section of Hydrology, and is published in these Transactions [pp. 677-680].

George H. Taylor states that the Forest Service, in cooperation with the Bureau of Agricultural Engineering, the Utah Agricultural College, and others, is carrying on an experiment on ground-water recharge in Davis County, Utah.

The United States Geological Survey has in progress several studies in New Mexico in cooperation with the State Engineer. A yearly inventory of water-levels in all irrigation-districts in which water is pumped from wells has been in progress for several years. This inventory has shown that in all of the districts the water-level is falling progressively and has indicated that in most of them the water is being taken from storage in extensive aquifers. The theory of pumping from such extensive aquifers is developed in a paper by C. V. Theis entitled "The significance and nature of the cone of depression in ground-water bodies," published in Economic Geology [December 1938]. The thesis of the paper is that the cone of depression around a pumping well must continue to expand areally until it reaches areas of previous discharge or areas where the recharge to the aquifer can be increased by a lowering of the water-level in those areas. The rate of lateral expansion of the cone of depression in non-artesian aquifers is slow, so that in very extensive non-artesian aquifers water may be taken from storage in the aquifer for a long time.

An investigation of the quantity of warm water available at Hot Springs, New Mexico, is in progress. The warm water in this vicinity apparently occurs in solution passages or joint planes in a limestone at rather shallow depths. The region is faulted and has been invaded by Tertiary volcanic rocks.

In an investigation by the Federal Geological Survey in the "Equus beds" Area, south-central Kansas, 19 cable-tool test-wells were put down in unconsolidated deposits to depths of 150 to 280 feet to determine the permeability of the beds and the quality of the water. In most wells there were several water-bearing beds of sand or gravel, separated by relatively impervious beds of clay. In order to determine static water-levels in different distinct water-bearing beds and to collect periodic samples of water from these deposits, from one to three 1-1/4-inch pipes with screened well points were left in each test-well. Before the six-inch casing was pulled, a point was set opposite a deep bed of sand or gravel, and covered with fine gravel. As the casing was pulled, the well was plugged, taking care to place clay opposite all thick beds of clay. When it was desired to set a second point at intermediate depth, the process was repeated. It would be possible to set points at four or more different depths in a single six-inch hole. After the wells were cleared by pumping, differences in head of as much as seven feet were measured.

During the year a comprehensive report on methods for determining the permeability of water-bearing materials was prepared by L. K. Wenzel, of the Federal Geological Survey, for publication as a Water-Supply Paper. The report includes a discussion of laboratory- and field-methods and applies several field-methods to four controlled pumping-tests made in Nebraska, and one pumping test made in Kansas. A bibliography of literature on permeability and laminar flow, by V. C. Fishel, including more than 500 references, is also included in the report.

Mr. Wenzel also reports in connection with the cooperative ground-water investigation in North Dakota that a water-stage recorder has been maintained on an artesian well in the Dakota sandstone which emits small amounts of gas at irregular intervals. The charts from the recorder show that the water-level in the Well rises slowly just before the gas is emitted and then declines sharply as the gas is released. The amplitude of the fluctuation is several tenths of a foot and the periodicy of the emission ranges from about two to 12 hours.

The Division of Ground-Water, of the United States Geological Survey, began an investigation in 1935 of the channel-storage method of measuring effluent seepage. The following statement in regard to this investigation has been prepared by V. C. Fishel. "The theory of the channel-storage method is as follows: During periods in which there is no overland-runoff, the flow of ground-water into the stream-system (effluent seepage or ground-water runoff) above any point on the trunk-stream is equal to the total discharge of the stream past that point minus the decrease or plus the increase in channel-storage. For strict accuracy, account would also have to be taken of evaporation from the water-surface, of the stream-system and possibly of other minor quantities. This investigation was started on the upper part of the drainage-basin of the Difficult Run, comprising an area of about one square mile, near Fairfax, Virginia.

"In the present investigation, the channel-storage of the Stream at different stages is determined by means of cross-section profiles and gage-height readings at 100-foot intervals. The data thus obtained are correlated with the rate of discharge at the master gaging-station as determined by the usual stream-gaging methods. Subsequently, the channel-storage at any time is ascertained from the record of the water-stage recorder at the master gaging-station by means of a channel-storage rating-table. It is, of course, recognized that a more complex installation will be required to obtain reliable records of the channel-storage of larger stream-systems, but the plan of work is to make first a detailed study of the method in a small unit-basin and later to apply the results to larger drainage-basins, with necessary modifications.

"The installations consist of a weir and water-stage recorder at the master gaging-station, 134 subsidiary gaging-stations for determining channel-storage, two recording rain-gages, and eight observation-wells, of which three are equipped with water-stage recorders. Automatic water-stage recorders are also installed on the stream in the vicinity of the observation-wells and at a gaging-station near the mouth of Difficult Run. A map showing the area under investigation and the location of the master gaging-station (Beecher stream-gaging station), rain-gages, and the observation-wells, is given in Geological Survey Water-Supply Paper 840 [p. 617]. A preliminary report of the investigation was given by Meinzer and others in a paper published in the Transactions of the American Geophysical Union [17th Annual Meeting, pp. 415-418, 1936]. The investigation is being continued by the Division of Ground-Water in cooperation with the Division of Water-Utilization. On account of the greater urgency of other work, progress on this project has been slow. Fifty-five sets of measurements of the gages have been made during the past year for use in developing a channel-storage rating-curve. A four-year record of the precipitation has been obtained by the Bacon rain-gage and a one-year record of precipitation has been obtained at the Manion rain-gage, which is across the basin from the Bacon gage. The master gaging-station was started in June, 1935, but damage by floods has resulted in the loss of some records from this station. The record has been complete since October 1937."

Students of the hydrology of limestone terranes will be interested in the logs of test-wells drilled along the route of the proposed Florida Ship Canal, and other data pertaining to the hydrologic problems involved in the construction of the Canal, which have been published in House Document 194, 75th Congress, 1st session [12]. The report contains graphic sections of test-borings which show many solution-cavities in the Ocala limestone, including some at depths of 34 and 42 feet below sea-level in test-holes 11 and 12 miles, respectively, offshore in the Gulf of Mexico. It also contains a map of the piezometric surface of the water in the Ocala limestone and graphs showing fluctuations of water-level observed during studies by the United States Army Engineers. To judge from reports received from different sources, the Army Engineers obtain ground-water data of several kinds in many of their investigations. It is to be hoped that more of these may be published, as have the data for the Florida Canal, in order that they may be available for study by ground-water hydrologists.

H. F. Blaney reports water-spreading investigations in California were continued by the Bureau of Agricultural Engineering in 1938. Some of this work is described in a paper by A. T. Mitchelson, entitled "Conservation of water through recharge of the underground supply" [Civ. Eng., March, 1939]. In this connection, reference may also be made to a paper by R. M. Roper, describing ground-water recharge from ponds maintained by the East Orange, New Jersey, Water-Department to increase the supply for its wells [13].

The largest program of ground-water investigations by the Federal Geological Survey is in Texas, in cooperation with the State Board of Water Engineers. At the present time seven major projects are in progress in different parts of the State, under the general direction of W. N. White. Some of the most interesting problems are described below.

The following statement in regard to an investigation of the ground-water supplies in the El Paso Area, which has been in progress since 1935, has been furnished by A. N. Sayre, who is in charge of the investigation:

"Pumping from wells on the upland plain or mesa, and in the Rio Grande Valley, which draw water from unconsolidated sands, began about 1904. A comparison of the total pumpage to the end of 1936 with the product of the volume of the cone of depression times the average specific yield of the material indicated that more than half, possibly three-fourths of the total amount of water pumped had been supplied by recharge to the ground-water reservoir. Since 1936 pumpage-data and water-level measurements have been systematically collected with a view to determining the safe yield of the ground-water reservoir. The pumpage from the wells has been measured or estimated for each month. In 1936 the depth to the water-level in about 40 selected wells was measured monthly. The record is not yet sufficiently long to permit drawing final conclusions as to the safe yield. The average daily pumpage was about 15,700,000 gallons in 1936, about 16,700,000 gallons in 1937, and about 16,200,000 gallons in 1938. The water-levels declined an average of about 1.95 feet during 1936 and 1.31 feet in 1937, and rose 0.78 feet in 1938. Forty-five wells were measured in 1938. The water-levels in about half of these wells rose during the year and in the other half declined. The wells in which the water-levels rose were situated near areas of heavy pumping and the amounts of the rise were relatively large, indicating that pumpage was considerably less in the period before the measurements were made than when the measurements of 1937 were made. The wells showing a decline, on the other hand, were mostly near the edges of the pumped areas, showing that the cones of depression continued to expand but the amounts of decline were small. A series of contour-maps representing the water-level in January of each year also shows that the cones of depression have continued to expand during the entire period.

"The El Paso City Water-Department has drilled a series of test-wells, in most of which electrical logs were made by the Schlumberger process. These logs appear to show that beneath the mesa highly mineralized water occurs beneath the fresh water. In Test-Well 8, which is about one-half mile east of Well 12, in the so-called Mesa Field, brackish water (containing between 300 and 700 parts per million of chloride) was found about 990 feet beneath the surface. In Test-Well 11, situated one-half mile east of Test-Well 8, brackish water was found at about 920 feet and salt water (more than 700 parts per million) was found at 1115 feet beneath the surface. Additional wells were drilled toward the east at half-mile intervals and encountered mineralized water progressively nearer the surface. In Test-Well 19, situated five miles east of Test-Well 8, according to the Schlumberger log, brackish water was encountered at 560 feet and salt water at about 775 feet beneath the surface. In this Well water samples were taken which substantially checked the Schlumberger determinations. With reference to a horizontal plane the zone of mineralized water rises toward the east at the rate of about 100 feet to the mile. Test-Well 20, one mile north of the mesa well-field, encountered salt water at a depth of about 900 feet. As yet no satisfactory explanation of the occurrence of the salt water has been found."

Mr. Sayre has also furnished the following statement in regard to ground-water conditions along the Balcones fault-zone:

"In the Balcones fault-zone water from streams and from rainfall enters the Edwards limestone in its area of outcrop, moves down the dip, and is discharged partly through wells, but chiefly through fault-springs along an irregular line, perhaps 20 miles wide, from Austin southwestward to San Antonio and thence westward to Del Rio, a distance of about 200 miles. General studies of the geology and ground-water in three counties covering about half of the area have been completed. Geological and hydrological investigations are being made in Kinney County, which is adjacent on the west to the areas already studied, and in Hays and Travis counties, to the east of them. Periodic measurements of water-levels in a large number of observation-wells ending in the Edwards limestone are being made. Stream-losses to the Edwards limestone are being measured on the Neuces and Frio rivers and the discharge of the springs is being determined. It is hoped by careful study of these data to establish the recharge-areas in which the principal recharge occurs for each of the springs."

A test was recently made by Penn Livingston which shows the large permeability of the Edwards limestone in some places. The test was primarily to determine the rate of yield of a well belonging to the San Antonio Public Service Company. The well is about 950 feet deep, 12 inches in diameter at the top, and had a static head of about 70 feet above the land-surface at the time of the test. The well flowed for seven days at the rate of 7,300,000 gallons a day. No lowering of the artesian pressure due to the flow was detected on a recording gage on a well only 24 feet from the test-well, nor in two wells ending in the Edwards limestone three-tenths and eight-tenths of a mile distant from it, respectively. The observation-well only 24 feet away from the flowing well passes through the same formations but is reported to have encountered "tight" limestone and yields only a small amount of water. The failure of this well to display a decline in artesian pressure may be due to the absence of a free connection through the limestone between the observation-well and the flowing well. Both of the more distant wells are capable of yielding large amounts of water and it has been suggested that the lack of a decrease in artesian pressure in them is due to the extremely cavernous condition of the limestone. It is believed that the pressure-head at the bottom of the flowing well is only slightly reduced when it is permitted to flow and that the loss of head is caused chiefly by friction of the large volume of water through more than 900 feet of casing."

In the High Plains of Texas the available supply of usable ground-water in the greater part of the region is derived from rainfall on the surface of the Plains. An investigation of the recharge and discharge--natural and artificial--of an area of about 9000 square miles in the High Plains led to the conclusion that the total natural discharge--which is an indication of the perennial safe yield of the water-bearing beds--was about 25,000 acre-feet a year, which is equivalent to the penetration of about one-twentieth of an inch of rainfall over the area. Some of the outstanding facts disclosed in this investigation are given in a paper presented by W. N. White at the meeting of the Section of Hydrology at Los Angeles in December, 1938, and published in these Transactions [pp. 32-35].

At Houston, prior to 1937, the artesian pressures had reached a stage of comparative equilibrium or displayed a very small annual decline. About March 1, 1937, a paper pump-mill was started near Pasadena, Texas, which required an average supply of well-water of about 19,000,000 gallons a day. This represented an increase of almost 40 per cent over the average daily draft by all the wells in the Houston-Pasadena area in 1935 and 1936. The effect of the sudden increase in pumpage on the water-levels in the area is being watched closely by measurements at regular intervals in numerous observation-wells widely scattered over the area. Exploratory drilling involving approximately 18,000 feet of drilling in ten test-wells with Schlumberger electric logs in each well, is receiving considerable attention. A special effort is being made from studies of the cuttings, core-samples, and sands brought up in the drill-stem tests to determine whether the resistance as recorded by the Schlumberger graph has any relation to the permeability of the sands. As a check, experiments are being made with the Wheatstone bridge to determine the electrical resistance of the drill-stem water at different depths and the resistance of drill-stem sand-samples as taken from the drill, and as screened into different sizes. In these tests the sands are saturated with the water which was in them originally. The tests with the Wheatstone bridge already indicate that the resistivity varies directly with the coarseness of the sands.

The attention of hydrologists is now focused on the meetings of the International Association of Scientific Hydrology, which is to meet during the Assembly of the International Union of Geodesy and Geophysics at Washington, D. C., September 4 to 15, 1939. The agenda of the Commission on Underground Water includes three "questions" on which papers are to be submitted by the adhering countries. For the United States the papers on these subjects have been prepared as follows:

Question No. 1--Circulation of water and of water-vapor, between the surface of the ground and the zone of saturation, by H. E. Middleton and W. E. Davis

Question No. 2--Definitions of the different kinds of underground water, by Charles H. Lee

Question No. 3--Determination of the runoff and physical conditions of flow of underground water in natural or altered ground, the flow being natural or induced, by L. K. Wenzel

In connection with discussions of definitions under Question No. 2, O. E. Meinzer has made certain suggestions, including several new terms, especially relating to distinctions between artesian and non-artesian water, to be applied to the nomenclature for international use. The purpose of his suggestions is in part to recognize definite distinctions which, however, have not been fully appreciated by some workers in hydrology, and in part to bring about a greater uniformity in usage of terms among the hydrologists of different countries. These he discussed at the annual meeting in 1939 of the Section of Hydrology of the American Geophysical Union at Washington; his statement is published elsewhere in these Transactions [pp. 674-677].

While reviewing Mr. Lee's report on the same question, namely, definitions of different kinds of ground-water, your Chairman has been impressed with the fact that there are a number of other terms used by ground-water hydrologists that should be defined, or redefined, by some recognized scientific organization in order that as wide an adoption as possible may be insured. This need arises in part from the fact that, as the science of ground-water hydrology has progressed there has been a sharper definition of the original concepts and new concepts have developed. There is evidence, for example, that many workers do not grasp the full significance of the term "piezometric surface;" nor do they fully understand the relation between the piezometric surface of an artesian aquifer and the water-table of a nonartesian aquifer. Considering the fact that continuous records of the fluctuation of water-level in many wells show that the water is almost always rising or falling, and that water is always moving, if only slowly, through most aquifers, the question may be raised as to whether the term "static water-level" is appropriate. There is also some lack of usage in the term "cone of depression." Some consider it to be the geometric surface represented by the piezometric surface around a discharging well. Others consider it, perhaps more properly from the mathematical viewpoint, to be "the geometric solid included between the water-table or other piezometric surface after a well has begun discharging and the hypothetical position the water-table or other piezometric surface would have had if there had been no discharge by the well" [14]. Other examples could be cited. It is suggested that a consideration of the clarification of usage of some of these terms may be undertaken in the future by the Committee on Underground Water of the Section of Hydrology of the American Geophysical Union in cooperation with the International Commission on Underground Water and a recently appointed International Commission on Nomenclature for the entire science of hydrology, of which Mr. Meinzer is a member.

During the year members of the Division of Ground-Water of the Federal Geological Survey prepared abstracts of about 80 reports and articles for inclusion in the United States section of the Bibliography published as a project of the International Association of Scientific Hydrology. Abstracts of a somewhat larger number of articles pertaining to ground-water hydrology were prepared for the Annotated Bibliography of Economic Geology.

In closing this report of the Committee on Underground Waters for the last year of the triennium, your Chairman wishes to express his appreciation to the members of the Committee for the support they have given him. The members of the Committee have been as follows: H. F. Blaney; Gordon M. Fair; Willard Gardner; C. S. Howard; F. H. Lahee; C. H. Lee; M. M. Leighton; O. E. Meinzer; A. M. Piper; A. C. Swinnerton; and David G. Thompson (Chairman).

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U. S. Geological Survey,
Washington, D. C.

## REPORT OF COMMITTEE ON DYNAMICS OF STREAMS, 1938-39

Lorenz G. Straub, Chairman

All members of the Committee on Dynamics of Streams have been quite active in the field of the Committee's assigned work and in immediately related activities. Individual members are represented on several of the other Committees of the Section of Hydrology of the American Geophysical Union and on Committees on related subjects of other organizations. This has been advantageous in the stimulation of cooperative effort in the field of the Committee's activity.

Last year nine reports of the Committee's membership were presented at meetings of the American Geophysical Union and published in its Transactions. Several other persons solicited by the Committee prepared papers for presentation at the Union's meetings. Numerous articles on stream-dynamics by the Committee's membership have also appeared in other publications. There have been no changes in membership of the Committee on Dynamics of Streams during the past year. The membership of the Committee is as follows:

K. Hilding Beij, National Hydraulic Laboratory, Bureau of Standards, Washington, D. C.
H. H. Bennett, Director, U. S. Soil-Conservation Service, Department of Agriculture, Washington, D. C.
Irving B. Crosby, Consulting Geologist, 6 Beacon Street, Boston, Massachusetts
John B. Drisko, 34 West Baltimore Street, Kensington, Maryland
H. V. Geib, Division of Research, Soil-Conservation Service, College Station, Texas
C. S. Howard, Chemist, U. S. Geological Survey, Washington, D. C.
E. W. Lane, Associate Director, Iowa Institute of Hydraulic Research, Iowa City, Iowa
L. M. Lawson, Commissioner, International Boundary Commission, First National Bank Building, El Paso, Texas
W. C. Lowdermilk, Chief, Division of Research, U. S. Soil Conservation Service, Washington, D. C.
Gerard H. Matthes, Mississippi River Commission, Box 363, Vicksburg, Mississippi
G. W. Musgrave, Experiment Station, Soil-Conservation Service, Washington, D. C.
Martin E. Nelson, Associate Engineer, U. S. Engineer Sub-Office, Iowa Institute of Hydraulic Research, Iowa City, Iowa

M. P. O'Brien, College of Engineering, University of California, Berkeley, California
R. L. Parshall, Colorado State College, Fort Collins, Colorado
G. W. Pickels, Department of Civil Engineering, University of Illinois, Urbana, Illinois
C. H. Pierce, Senior Engineer, U. S. Geological Survey, Washington, D. C.
C. E. Ramser, Watershed and Hydrologic Studies, U. S. Soil Conservation Service, Washington, D. C.
William W. Rubey, U. S. Geological Survey, Washington, D. C.
Fred C. Scobey, U. S. Department of Agriculture, Room 219 P. O. Building, Berkeley, California
Lorenz G. Straub (Chairman), University of Minnesota, Minneapolis, Minnesota
Roy N. Towl, Consulting Engineer, 506 South Fifty-seventh Street, Omaha, Nebraska
A. C. Trowbridge, Department of Geology, University of Iowa, Iowa City, Iowa
Herbert D. Vogel, Fort Belvoir, Virginia
H. H. Wheaton, Department of Mathematics, Fresno State College, Fresno, California
N. E. Winters, State Agricultural College, Stillwater, Oklahoma

New Sub-Committee on Land-Forms--A concerted effort was started on the subject of "Land-forms as related to hydrology, geology, and dynamics of streams." For this purpose a Sub-Committee was appointed consisting of I. B. Crosby (Chairman), E. W. Lane, G. H. Matthes, W. W. Rubey, and L. G. Straub, ex officio.

At a meeting in Washington in 1938, attended by four of the members of the Sub-Committee on Land-Forms, it was decided to choose as the first problem the study of river-meanders for the purpose of determining under what conditions rivers meander and what factors control the size and shape of the meander. It was recognized as necessary to study and evaluate many factors, including slope, depth, shape of channel, nature of bed, resistance of bed and banks to erosion, velocity, characteristics of flow, such as steady or widely fluctuating, and quality and character of sediment-load, including both bed-load and suspended load.

In line with this first objective, a study is in progress of the Mississippi River below Cairo to ascertain whether levee-confinement has interfered with the natural aggrading processes. Gerard H. Matthes has been conducting a study for some time to determine how much the river-profile has changed since levees were built. The subject is of considerable importance, as the opinions among engineers and geologists are far apart as to whether the lower Mississippi is continuing to elevate its bed and banks as heretofore or whether this process has stopped or even become reversed.

It is proposed eventually to make a comparison of conditions of meanders of the lower Mississippi with other streams on the Coastal Plain which meander, and with similar streams which do not meander. Consideration is also being given to the effect of cut-offs on the regimen of rivers. A review of the regimen of the Missouri River is being conducted by Lorenz G. Straub, various related studies by E. W. Lane, and a study of the meanders in the Big Thompson River in Estes Park, Colorado, by C. J. Posey. Of the papers on dynamics of streams presented at the 20th Annual Meeting of the Section of Hydrology of the American Geophysical Union, two are in line with the Sub-Committee's work. One concerns "Model-experiments of directive energy of a river," made at the United States Waterways Experiment Station, and involves a study of the development of the serpentine form of river-channel; the other concerns the relation of suspended to bed-material in rivers.

Research--Research in dynamics of streams has been progressing steadily. The importance of closer correlation of the theoretical approach with experimental studies is becoming generally recognized. Unquestionably, in the course of the next few years outstanding developments are to be expected in the treatment of stream-dynamic problems involving sediment-transportation, erosion, wave-occurrences, and the like. Valuable contributions have already been made in accounting for the transportation of sedimentary materials in the light of recent developments in the theory of fluid turbulence.

Several focal points in the exchange of information relative to hydraulic research are adding materially in the apparent progress. Following the lead of the National Hydraulic Laboratory of the Bureau of Standards, the status of current work in hydraulic research is now being quite systematically published and distributed for practically the entire world. Bulletins are now issued annually in much the same form (1) by the National Bureau of Standards, Washington, D. C., for research in the United States, (2) by the International Association for Hydraulic Structures Research for projects throughout Europe with the exception of Russia, and (3) by the U.S.S.R. Commission for Exchange of Hydraulic Laboratories Research Results, Leningrad, for Russia. The services of these three organizations have been an invaluable aid to investigators throughout the world.

The work of several committees within and outside of the organization of the American Geophysical Union borders on that of this Committee; the work of these committees advantageously supplements each other and for the most part does not in any way result in duplication of efforts. Thus, within the Union there are particularly the Committees on Runoff and Rainfall, the Special Committee on Flood-Waves, and the Advisory Committee on Soil-Conservation Research. There are also the National Research Council's Interdivisional Committee on Density-Currents, the Special Committee on Hydraulic Research of the American Society of Civil Engineers, and the National Research Council's Committee on Sedimentation.

A number of hydraulic laboratories distributed throughout the country and various Governmental bureaus have been especially active in research coming within the province of interest and assigned work of the Committee. The present status of much of this work is quite well summarized by the Bureau of Standards [Current hydraulic laboratory research in the United States, Nation. Bur. Stand. Hydraulic Lab. Bull., Series A, Bull. 7, January, 1939].

Other Meetings--In addition to the annual program of the Section of Hydrology of the American Geophysical Union, several other conferences involve more or less concerted programs in the field of stream-dynamics. These include the regional meetings of 1938 reported on in the *Transactions* [pp. 587-745]. There are also several International meetings of importance. One of these was the Baltic Hydrologic Conference which took place in Lübeck and Berlin in August, 1938. The countries taking part in the meeting were Danzig, Denmark, Esthonia, Finland, Germany, Latvia, Lithuania, Norway, Poland, and Sweden. Seventy-four reports of this Conference were published, most of which were on various river hydraulic problems, such as river-ice and winter regimen, the formation and development of river-rapids, erosion-occurrences at bridge cross-sections, the influence of wind upon flow-resistance in broad streams, etc.

During September, 1939, at Washington, D. C., in connection with the Assembly of the International Union of Geodesy and Geophysics, a program is being arranged for the Commission of Potamology. The program is set up in three questions for discussion by representatives from various countries. Question 1 concerns evaporation, question 2 concerns flood-forecasting, and question 3 concerns stream-dynamics. In more detail, the third item may be phrased as "The study of the conditions of transportation of solid load in streams with a bed of loose sediment (alteration of the shape of the bed-formation of banks, sills, and deeps, namely, deposition and erosion). Laws of transport of material, especially with regard to the speed and depth of the water and to the specific gravity and dimensions of the material, obtained from tests in the laboratory and from direct observations of natural streams." Papers to be presented at the meetings of the Commission of Potamology in Washington then have already been received from the following countries: Belgium, Denmark, England, Finland, France, Germany, Holland, Latvia, Poland, and Sweden.

Another important International Conference this year will be that of the International Association for Hydraulic Structures Research. The meeting of the Association will be held in Liege the last part of September, 1939. The principal problems to be treated at this meeting will be as follows: (1) Bed-load transportation research; (2) Scour below weirs; and (3) Hydrodynamics of locks.

Review of literature on dynamics of streams--In accordance with the custom followed in the past, a review has been prepared by the Chairman of the Committee relative to publications which have appeared during the past two years in the field of dynamics of streams. This review as far as possible has been with reference to works abroad as well as in America. The number of works which have appeared in recent years is an indication of the continued and accelerated activity which is taking place. This bibliography follows.

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# REPORT OF SPECIAL COMMITTEE ON FLOOD-WAVES, 1938-39

Lorenz G. Straub, Chairman

The Special Committee on Flood-Waves is in its second year, having been established in June, 1937, by the Executive Committee of the Section of Hydrology as a culmination of earlier informational conferences of persons concerned with hydrologic investigations, particularly for the Federal Government. It was recognized that the data and analytical studies regarding various flood-wave phenomena are exceedingly fragmentary. This Committee has served as a focal point for discussion of flood-wave phenomena and the making and dissemination of available information.

The work of the Committee has been carried on primarily through sub-committees and special assignments to individual members and their colleagues in this particular field. The membership of the Special Committee on Flood-Waves has remained the same from the time it was established and is as follows:

Merrill Bernard, U. S. Weather Bureau, Washington, D. C.
H. N. Eaton, Hydraulic Laboratory, National Bureau of Standards, Washington, D. C.
R. S. Goodridge, U. S. Soil Conservation Service, Washington, D. C.
Robert E. Horton, Consulting Hydraulic Engineer, Voorheesville, New York
Ivan E. Houk, U. S. Bureau of Reclamation, Washington, D. C.
W. G. Hoyt, U. S. Geological Survey, Washington, D. C.
Hans Kramer, U. S. Engineer Corps, Conchas Dam, New Mexico
F. T. Mavis, College of Engineering, University of Iowa, Iowa City, Iowa
M. P. O'Brien, College of Engineering, University of California, Berkeley, California
Lorenz G. Straub (Chairman), University of Minnesota, Minneapolis, Minnesota
H. A. Thomas, Carnegie Institute of Technology, Pittsburgh, Pennsylvania

The Sub-Committees are as follows:

(1) Governmental Activities: W. G. Hoyt (Chairman); Merrill Bernard; R. S. Goodridge; Ivan E. Houk; Hans Kramer

(2) Bibliography: F. T. Mavis (Chairman); H. N. Eaton; R. E. Horton; R. S. Goodridge; M. P. O'Brien

(3) Current Investigations: H. A. Thomas (Chairman); H. N. Eaton; F. T. Mavis; M. P. O'Brien

Attention is here called to last year's report of the Special Committee on Flood-Waves, which presents in somewhat more detail than here the objectives of the Committee, the functions of the Sub-Committees, and the assignments to individual members; the report also contains six appendices [Amer. Geophys. Union Trans., 1938, pp. 355-386]. The latter were as follows: Appendix A--Report of activities of Sub-Committee Relating to Governmental Activities of the Special Committee on Flood-Waves, May 1938, by W. G. Hoyt, Chairman; Appendix B--Report of Sub-Committee on Bibliography of Special Committee on Flood-Waves, by F. T. Mavis, Chairman; Appendix C--Report of Sub-Committee on Current Investigations of Special Committee on Flood-Waves, by H. A. Thomas, Chairman; Appendix D--Rain wave-trains, by Robert E. Horton; Appendix E--Seddon's and Forchheimer's formulas for crest-velocity of flood-waves subject to channel-friction control, by Robert E. Horton; Appendix F--A study in the theory of flood-waves, by Elmer E. Moots.

The present Report supplements that made a year ago. The important additional contributions here presented are by the Sub-Committees. These contributions have been prepared by Professor F. T. Mavis and Professor H. A. Thomas, Sub-Committee Chairmen, and form appendices A and B of this Report.

By the work of the past two years the Committee has essentially served the function of summarizing the status of knowledge on flood-waves and of presenting a survey of the distribution of activities in this field in the United States. At the time of its establishment there was considered the feasibility of having the Committee serve as an advisory committee for cooperative studies by Governmental bureaus in this field. The latter function has not been crystallized. At present, therefore, it is recommended that the Executive Committee of the Section of Hydrology of the American Geophysical Union consider the disposition of this Committee: Whether it is (1) to function as a research committee; (2) to serve as an advisory committee to associated Governmental bureaus in accordance with the purpose originally considered; or (3) to be dissolved with its research activities distributed among existing research committees. Its field of research falls more particularly within that of the Committee on Dynamics of Streams and the Committee on Runoff.

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## APPENDIX A--REPORT OF THE SUB-COMMITTEE ON BIBLIOGRAPHY

F. T. Mavis, Chairman

The Sub-Committee on Bibliography, appointed by the Chairman of the Special Committee on Flood-Waves on September 2, 1937, consisted of H. N. Eaton, Robert E. Horton, R. S. Goodridge, M. P. O'Brien, and F. T. Mavis (Chairman). It was instructed to prepare "an annotated bibliography of classical and recent works on flood-waves . . . probably giving consideration to unanalyzed experimental data as fully as to mathematical treatments." A progress-report of this Sub-Committee was published in the Transactions [Amer. Geophys. Union, 1938, pp. 362-363].

Submitted herewith is an "Annotated bibliography and abstracts of flood-waves and related phenomena" covering approximately three hundred references. About one-half of these have been checked and abstracted or annotated in the following "Bibliographical abstracts." The balance of this Report is devoted to references which have been gathered from bibliographic sources but have not been checked in detail to determine whether they pertain to flood-waves and related phenomena. The advisability of preparing informative abstracts of articles may not be self evident and the task of abstracting the literature pertinent to flood-waves may become burdensome to a small committee. Shall the work of abstracting the literature be further distributed? How can the material best be made available to members interested? On these questions the Sub-Committee desires advice and suggestions of the Special Committee on Flood-Waves.

The Chairman is indebted to a score or more of engineers who submitted abstracts of papers, annotations, or lists of references. Usually the name or initials of the abstracter or annotator appears at the end of each completed abstract or annotation. Annotations indicated by the abbreviation "Calif." were prepared by Joseph H. Sorenson working on Works Progress Administration Project No. 5970 under the direction of M. P. O'Brien and R. L. Stoker in the Fluid-Mechanics Laboratory of the University of California. Others who cooperated in the Sub-Committee project include O. J. Baldwin, F. L. Blue, Jr., John B. Drisko, G. H. Dunstan, H. N. Eaton, R. S. Goodridge, R. E. Horton, J. W. Howe, G. H. Keulegan, E. W. Lane, H. C. Lay, Elmer E. Moots, Samuel Shulits, L. G. Straub, Max Suter, and Chilton A. Wright.

### Bibliographical abstracts

A. M. ANGELINI, Sulla propagazione delle perturbazioni nei corsi d'acqua (Propagation of perturbations in water courses), Elettrotecnica, v. 23, pp. 486-494, August 25, 1936.

Theoretical and mathematical analysis of laws of propagation of periodic and non-periodic changes in discharge and in depth of water in open channels; application of Heaviside operational calculus; graphical method of solution of problem involving propagation of disturbances in water course.--Calif.

H. ARAKAWA, Generalized Green's law on wave motion in a canal of variable section, Geophys. Mag., Tokyo, v. 7, pp. 319-325, November 1933 (in English).

From the generalized Green's law it is found that the amplitude of waves traveling up a canal becomes greater the gentler the slope of the bottom; the more gradual the variation of the breadth of the canal the greater the amplitude of the waves; the amplitude increases more rapidly in the case of short than of long waves; and lastly, assuming small oscillations, the amplitude on a sloping shore depends on the slope of the bottom as well as the width of the channel.--Calif.

M. BACHET, Note sur la propagation et l'annonce des crues (Note on the propagation and prediction of flood-waves), Annal. Ponts et Chaussées, v. 104, pp. 409-465, 1934.

The historical development of flood-prediction on the Loire by the Federal Service is described. The early predictions were by the double-column tabular method of giving the effects of flood-waves from two separate sources from which the maximum could be obtained. On the basis of an extended mathematical analysis, a method of graphical determination of flood-heights by the use of transparent scales was developed. The effects of attenuation, overbank-storage, eddies at confluence, and multiple tributaries are analyzed separately and reduced to a straight-line diagram. In doing this for a large system of tributaries considerable judgment is necessary. An illustration is given of the application of this method to floods on the lower Loire River at Montjean, and the results are compared with actual floods. The positive and negative errors were found to be evenly divided, in the neighborhood of 0.1 meter and did not exceed 0.25 meter.--Chilton A. Wright

H. K. BARROWS, Velocity of flow in natural streams, Amer. Geophys. Union Trans., pp. 339-349, 1932.

Studies of a 230-mile reach of the Delaware River between Trenton, New Jersey, and Downsville, New York, included comparisons of observed and computed times of transit of water. Port Jervis, New York (drainage-area 3070 square miles), approximately midway on the River between Trenton (drainage-area 6800 square miles)and Downsville (drainage-area 380 square miles), was taken as the index-station and seven assumed index-flows from 1500 to 5900 sec-feet per square mile were used as the basis for analysis. Many cross-sections of the River were taken in the 230-mile reach and stage-discharge curves were made for each profile-station. Concordant profiles based on different rates of flow at the index-station were constructed to harmonize observations of discharge and profile. Times of transit were computed and corrected on the basis of float-measurements which were made simultaneously in five sections of the River averaging about 50 miles each in September, 1929, and March, 1930. The former float-observations were made at an average stage representing 0.45 sec-feet per square mile at Port Jervis, and the latter at a stage representing 3.6 sec-feet per square mile. Computed times of transit were materially longer than those based upon the float-measurements, and the computed times were corrected to make them consistent with the float-runs in September. Analyses of flood-wave velocities by L. K. Sherman showed that the flood-wave velocity was approximately double the velocity of ordinary flow at the rising stage of the River. Observations of wave-velocities in the River below the Hawley Plant of the Pennsylvania Power and Light Company on Wallenpaupack River checked the computed time of flow by Sherman formula fairly well.--F.T.M.

A. B. BASSET, Treatise on hydrodynamics, Cambridge, Deighton, Bell and Co., v. 1 and 2, 1888.--R.E.H.

J. BAURAND, Periodic waves on the surface of water, C. R., v. 193, pp. 992-994, November 23, 1931.

In continuation of previous work [see abstract 2898, 1928], the author discusses experimental values of the velocity of propagation of small waves on water contained in a dish. Kelvin's formulas for the velocity and period of ripples are verified approximately by the results.--Calif.

M. BAZIN, Recherches expérimentales sur la propagation des ondes, Mem. Sav. Ac. Sc. Insti. Impér. France, Paris, v. 19, pp. 495-652.--R.E.H.

Nathaniel BEARDMORE, Manual of hydrology, Waterlow and Sons, London, 1862.

This book contains tables giving velocity of tides and tidal waves in the Tyne, Clyde, Mersey, and Severn rivers, and a discussion of the bore of the River Seine.

E. S. BELLASIS, Hydraulics with working tables, E. P. Dutton and Co., New York, 3rd Ed., pp. 328-333, 1922.

E. S. BELLASIS, Some record runoffs from Indian Hill catchments, Eng., v. 123, pp. 5-7, January 7, 1927.

The Mianwali Torrent in the Sub-Himalayan Hills has a drainage-area of 0.83 square miles. On September 4, 1908, a flood of 4,056 sec-feet passed down a channel approximately 250 feet wide and 1.1 to 2.6 feet deep. Float-velocities exceeded 13 feet per sec and the surface-gradient was about 1:70. A striking feature of this flood was the occurrence of large waves three to four feet high which were highest in midstream and less marked toward the banks with crests running generally transverse to the stream. The waves became less marked at the extreme height of the flood and there was little or no foam. They died away as the flood fell. It is probable that the sand-bed of the Torrent itself became formed into a series of waves which, however, did not exist when the flood had run off.--H. C. Lay

W. BERG, Ueber den Modellmasstab in den Wasserbaulaboratorien (Scale of models in hydraulic laboratories), Bauingenieur, v. 12, No. 32-33, pp. 576-578, 6 figs., August 7, 1931.

Discussion of Glushkov law stating that square root of width of model divided by its average depth is constant, depending on nature of bottom; use of models with vertical and horizontal scales not equal in study of flood-waves in Bay of Finland, near Leningrad.--Calif.

E. BERTIN, Données théoriques et expérimentales sur les vagues et les roulis, Mém. Soc. Nat. Sc. Natur. et Math. Cherbourg, Paris and Cherbourg, v. 22, pp. 161-227.

Bertin gave a detailed explanation of the theory in Mem. Soc. Imp. Sc. Nat. Cherbourg, 1869-1870, v. 15, pp. 5-44, and further _ibid_., v. 17, pp. 125-128, 209-352, 1873. The paper cited is a continuation of the article of 1873.--R.E.H.

M. A. BIOT, Quadratic wave equation: Flood waves in a channel with quadratic friction, Nation. Acad. Sci. Proc., v. 21, pp. 436-443, July 1935; see Sci. Abs. A., v. 38, p. 984, 1935.

An exact solution of the equation of propagation of waves with quadratic damping is obtained. It is shown that high-amplitude waves are more quickly damped, etc.--Calif.

F. L. BLUE, Jr., J. K. Herbert, and R. L. Lancefield, Flow around a river bend, investigated, Civ. Eng., v. 4, pp. 258-260, May 1934 (M.S. thesis, University of Iowa, 71 pp., July, 1933).

Observations of a sharp bend on the Iowa River led to the following conclusions: The water-surface at the outside of the bend is superelevated over that at the inside approximately

$$\frac{v^2b}{gr} \text{ or } \frac{v^2}{g}\left\{\frac{20r}{3b} - \frac{16r^2}{b^3} + \left[\left(\frac{4r^2}{b^2} - 1\right)^2 \log_e\left(\frac{2r + b}{2r - b}\right)\right]\right\}$$

Water near the surface flows toward outside of bend, while that near the bottom flows toward the inside, resulting in helicoidal flow. The longitudinal water-surface profile at the inner bank drops rapidly at the upstream end of bend and is almost level at the lower end. The profile at the inner bank flattens, or sometimes even rises, at the upstream end and drops rapidly at the downstream end. Velocities are high where longitudinal profiles are steep and are usually greatest near the outer bank at the downstream end of the bend, while velocities are low where slopes are flat. Bends tend to move progressively downstream through erosion at points of high velocity and deposition at points of low velocity. Bibliography has nine entries.--F. L. Blue, Jr.

L. BONNEAU, Etude sur les ondes stables dans les canaux et cours d'eau (Study of stable waves in canals and water-courses), Annal. Ponts et Chaussées, pp. 273-279, 1922.

A study is made of fixed and traveling waves in canals where the wave-length is generally not greater than the depth of water, except for the case of a solitary wave. The equation for a solitary wave is shown to be only a special case of the general equation for permanent waves. The assumption is made that the liquid portions of the waves are displaced parallel to themselves such that the particles trace homologous trajectories with regard to the bed. An expression is derived for permanent waves, with provision for the resistance of the bed and the excess of surface slope over bed slope.

$$\frac{h^2}{2} + \frac{h_1h_0{}^2}{3}\left[\frac{\partial^2h}{\partial x^2} - \frac{1}{h}\left(\frac{\partial h}{\partial x}\right)^2\right] - \frac{P_o}{g} = h_1h_o - \frac{h_1h_o{}^2}{h}$$

where h = depth at any point, $h_o$ = depth at upstream section, $h_1$ = depth at downstream section, x = distance from upstream section, and $P_o$ = total pressure against the upstream liquid cross-section exerted in the downstream direction. For a solitary wave with a velocity of propagation $v = \sqrt{gh_1} + u_o$, the above equation reduces to $z = 2f/(1 + \cosh \mu x)$, where $\mu = (1/2h_o)(\sqrt{3f/h_1})$, $z = (h - h_o)$, $f = (h_1 - h_o)$, g = acceleration of gravity, and $u_o$ = initial mean velocity. For a horizontal channel $u_o = 0$ and $v = \sqrt{gh_1}$ as found by Bazin. The impossibility of the occurrence of negative solitary waves is proven. Solitary waves depend upon only one parameter (height), while oscillating waves depend on two (height and length). Roll-waves on water-courses are very similar to surf-waves of the ocean. Roll-waves take up differences of energy between successive sections in the same stream having widely-different characteristics. Mr. Roussilhe found surges of this nature upon the Congo River. Wind produces roll-waves on the surface of water. This is more pronounced for quiet water than flowing water.--Chilton A. Wright

D. BONVICINI, Propagation of perturbations in a stream with free surface, Elettrotecnica, v. 21, pp. 652-656, October 5, 1934 [see Sci. Abs. B, v. 37. p. 692, 1934].

The problem of small oscillations in the mean velocity and head of water in a stream flowing with a free surface is studied. The loss of energy through friction is estimated according to the formula of Strickler, and account is taken of any variation in the mean radius, etc.--Calif.

J. BOUSSINESQ, Théorie de l'intumescence liquide appelée onde solitaire ou de translation, se propageant dans un canal rectangulaire (Theory of the liquid intumescence called a solitary wave or a wave of translation propagated in a channel of rectangular cross-section), C.-R., v. 72, pp. 755-759, 1871.

The author gives the theoretical treatment of the laws of waves observed by J. Scott Russell and by Bazin in sensibly horizontal rectangular channels of indefinite length, containing a liquid of constant depth. There is given also the derivation of a formula which Bazin deduced experimentally to calculate the velocity of advance of an increment-wave produced by a constant inflow in a channel initially containing a still body of liquid. For the solitary wave, the velocity of advance $\omega$ is given by $\omega^2 = g(H + h_1)$, where H is the depth of the undisturbed liquid and $h_1$ the height of the crest above the undisturbed level. The shape of the wave is given by

$$4h_1 = \left[2 + e^{\sqrt{\frac{3h_1}{H^3}}\,(x - \omega t)} + e^{-\sqrt{\frac{3h_1}{H^3}}\,(x - \omega t)}\right]h$$

where $\omega t$ is the abscissa corresponding to $h = h_1$, and h is the height of the wave at the point x. The volume of the wave per unit width is $4\sqrt{H^3h_1/3}$. For the increment-wave the velocity of advance is found to be $\omega^2 = g(H + 1.5\ h_o)$, where $h_o$ is the constant height of the incoming liquid running over the initial body of liquid.--G. H. Keulegan

J. BOUSSINESQ, Théorie des ondes liquides périodiques, Mém. prés. par divers sav. à l'Ac. Sci., v. 20, pp. 509-615, 1872.--R.E.H.

J. BOUSSINESQ, Essai sur la théorie des eaux courantes (Treatise on the theory of flowing water), Mémoires pres. p. divers sav. à l'Acad. Sci., v. 23, 1877.

The third and the last part of the memoires [pp. 242-528] is devoted to gradually-changing non-permanent motion. The treatment is essentially mathematical. Often reference is made to experiments in the laboratory or to observations made on natural water-courses for the purpose of corroborating the author's theoretical results. The author's various results, in themselves important and derived with undisputable rigor, are too numerous to be reproduced conveniently. Some of the general problems treated are: (1) Waves of small height in a channel when the resulting flow differs little from the basic permanent flow; (2) waves with surfaces of large curvature and the velocity of propagation of an intumescence in such waves (the distinction between the wave-velocity and the velocity of propagation of intumescence play a great rôle in the author's major analysis); (3) the form, energy, moment of instability, and other aspects of the solitary waves; (4) the effect of non-uniformity of velocity, of slope, and of friction on the velocity of propagation of an intumescence and on the mean velocity in a section; (5) the quasi permanent regime of floods in large rivers.--G. H. Keulegan

E. I. BROWN, The flow of water in tidal canals, Trans. Amer. Soc. Civ. Eng., v. 96, pp. 749-813, and discussion pp. 814-834, 1932 [see Civ. Eng. Abs., v. 47, pp. 166-167, 1931].

The author gives a very complete summary of the theories that have been put forward at various times and indicates their limitations. He proposes a new theory which assumes the reflection of the canal-wave from the basin or reservoir which is fed by the canal, and he states that the degree of reflection will be governed not merely by the canal itself, but also by the basin.--Calif.

J. M. BURGERS, Excitation of waves in a canal by motion of a transverse boundary, Zs. angew. Math. Mechanik, v. 13, pp. 67-71, April, 1933.

The excitation of stationary waves in an infinite channel filled with fluid, by the motion of a transverse wall bounding the channel at one end is discussed mathematically.--Calif.

W. BURNSIDE, On the modification of a train of waves as it advances into shallow water, Proc. Math. Soc. London, v. 14, pp. 131-133.--R.E.H.

A. L. CAUCHY, Théorie de la propagation des ondes à la surface d'un fluide pesant d'une profondeur indefinie (Theory of the propagation of waves at the surface of a heavy fluid of unlimited depth), Mémoire pres. p. divers Savants à l'Acad. R. Sci. l'Inst. France. Sci. Math. et Physique, v. 1, pp. 3-312, 1827.

The author considers the following problem: A mass of liquid subject to the force of gravity, initially at rest, and of indefinite depth is put in motion by a given cause. He inquires as to the form of the free surface of the liquid and the velocity of the particles situated on the surface at some definite time. The solution consists of three parts. In the first part are deduced the equations expressing the initial state of the fluid when the form of the initial free-surface and the forces acting on it are given. In the second part are given the equations which determine for any time whatever of the motion the state of the liquid and that of the surface. In the third part, the author establishes the general laws which result from the formulas given in the second part and determines the numerical value of the constants entering in the expressions of these laws. The main theme is developed on pages 3-124. The derivation and demonstrations of various analytical formulas in the form of notes are given on pages 124-313. This paper was awarded the mathematical prize of the Royal Academy for the years 1815 and 1816.--G. H. Keulegan

M. CHARY, Influence du calibrage partiel d'un cours d'eau sur la propagation des crues (Influence of improvements in a water-course on the propagation of flood-waves), Annal. Ponts et Chaussées, v. 104, pp. 394-399, 1934.

The object of this study was to determine what effect improvement of a river-channel for the reduction of flood-stages at one point had upon corresponding river-stages at stations downstream. A graphical analysis is given, based upon two successive stations along a river, at which the stage-discharge relation and the inundation-volumes are known. Discharge-time curves for a flood are drawn for the upstream station in relation to the downstream station, both before and after the improvements are made. The volume of inundation is determined in each case for a flat flood-wave and for a sharp-peak flood-wave. An example was given at Beuvron where the river-valley inundation was reduced half by the improvements, without increasing the flood-stage downstream from Beuvron by an appreciable amount.--Chilton A. Wright

M.COLLET, Note sur la prevision des crues, Annal. Ponts et Chaussées, pp. 37-46, 1937.--H.N.E.

J. W. CONWAY, Surges of the Tieton Canal, Trans. Amer. Soc. Civ. Eng., v. 71, p. 179, 1911.

This paper describes flow-conditions in a long winding artificial channel, consisting for the most part of an open section but with some tunnels. The cross-section of the open section was somewhat more than semi-circular with a radius of about four feet two inches; that of the tunnels was circular with a radius of about three feet. The slopes were 0.00165 and 0.0045 for open section and tunnel, respectively. Reinforced concrete construction with smooth surface. The flows were measured with current-meters. "The flow ... did not seem to obey any of the common hydraulic laws. There were a number of points where the water was heaped up and thown into considerable turmoil without any apparent cause. These points ... occurred at regular intervals, regardless of curves or tangents, and in fact were somewhat more noticeable on long tangents than at other places, ... there were traveling surges of water which worked their way slowly down the canal.... . There were also quickly changing high and low points... . There were places where the depth was not over three feet for a stretch of 50 to 75 feet, and other places ... where the depth was five feet or over. ...the water ... very often heaped on the inside instead of the outside of the curves."--Herbert N. Eaton

CORIOLIS. Mémoire sur l'établissement de la formula qui donne la remous, Annal. Ponts et Chaussées, I sem., pp. 314-335, 1836.--H.N.E.

Vaughn CORNISH, Progressive and stationary waves in rivers, Eng., v. 84, pp. 118, 284, 347, July 26, 1907.

The paper describes roll-waves (also called freshets and spates) on the rivers Tees and Ure (England), the Nile (Egypt), and the Nikko (Japan). It is stated that uniformity of depth in the cross-section is essential for the persistence of such a wave. If the channel consists of a deep central groove with shelving banks, the waves will change direction and lose energy by breaking on the shores. A river consisting of alternate pools and shallows is favorable to the formation of roll-waves. Small wedge-shaped solitary waves flowing down a precipitous cliff at Grindelwald are described. Also waves in a 14-inch wide conduit having a slope of 1:2 at Territet (Lake of Geneva). Here the roll-waves existed for low flows but not for large flows. Roll-waves in steep open channels at Grünbach and at Guntenbach are also described. Other types of waves in rivers and estuaries are discussed.--Herbert N. Eaton

Vaughn CORNISH, Waves of the sea and other water waves, London, Edit. 1910, p. 273.

Vaughn CORNISH, Ocean waves and kindred geophysical phenomena, Cambridge Univ. Press, Cambridge, 1934.

The third chapter of the book deals with bores and progressive waves in rivers. The presentation is expository. The creation of a progressive wave from a stationary one, which the author had occasion to observe in the Rapids of Niagara, is described. Its cause is attributed to the current suddenly becoming slower than the wave. In discussing the roll-waves of shallow waters, the following remark is made regarding the Grünnbach rolls which the author observed in 1904: "The excess velocity of these rolls over that of the current is in accordance with the formula given by J. Scott Russell for the velocity of solitary waves. The friction of the bottom is regarded as the origin of the roll-waves." The author attributes the occurrence of short waves in the mouths of tidal rivers to the entry into the river of tidal bores with moderate frontal slopes.--G. H. Keulegan

V. CORNISH, Tidal bores which assume the form of a group of short waves, R. Astr. Soc., Month. Notices Geophys., Supp. v. 3, pp. 183-190, January 1934 [see Sci. Abs. A., v. 37, p. 130, 1934].

The author supplies details regarding the tidal bores of the Severn and Trent [Mon. Notices R. Astr. Soc.].--Calif.

C. C. CRAGAN, Time required for water from Roosevelt Reservoir to reach Granite Reef, Eng.-Contracting (water-works issue), pp. 406-409, February, 1923.--R.E.H.

DARCY and BAZIN, Recherches hydrauliques, deuxieme Partie, Paris.

Experiments on a flume about 6.5 feet wide, two feet deep, and more than 1000 feet long. Experiments on a navigation-canal, 3000 feet long and 30 feet wide with 3-foot depth of water. Adoption-formulas derived by Russell with some modifications.--H. C. Lay

H. A. H. DeRONDE, Flood warning on the River Meuse, De Ing. (Bonev-en Waterbonwkunde), v. 48, pp. 37-42, ("De Ingenieur" The Hague) [see Civ. Eng. Abs., v. 56, pp. 160-161].

Tables are given which indicate how a certain rise in the headwaters can be used to predict floods (within a few hours) in the downstream waters.--Calif.

Ph. DEYMIE, An account of the propagation of elongated intumescences, Bull. Permanent Intl. Ass. Navigation Cong., No. 20, pp. 63-70, 1935.

The differential equations of the unsteady flow are reduced to an Ampere-Monge equation. It is deduced from the characteristics of the later equation that if there is initially a uniform regimen characterized by a velocity $u_0$, a depth $h_0$, and a quantity $q_0$, the velocity $v_0$ of the front of an intumescence is $v_0 = u_0 + \sqrt{gh_0}$. This relation is independent of the shape and the height of the intumescence and of the extent of the friction. The propagation of discontinuities in q and h obey the same law. The law of decrease in the frontal height of a discontinuous intumescence is not analyzed. The law of attenuation of the frontal height h for an intumescence for which the flow superposed on the initial regimen is constant and equal to $q_0$ is $h = (q_0'/v_0)e^{-as}$, where a is a function of bed-slope i, of $u_0$ and $h_0$, the velocities and the depths of the primitive uniform regimen, and s is the distance traversed by the front. There can be no steep back face to an intumescence produced by a suddenly applied constant-excess flow of short duration.--G. H. Keulegan

John B. DRISKO, Report on wave studies, on file with Civ. Eng. Dept., Mass. Inst. Tech., 1933.

This report contains a summary discussion of various types of waves, for example, solitary, tidal, oscillatory, which is followed by a description of experiments made in a small channel. The experimental work covered solitary waves, waves propagated into a channel by tides, power- (increment-) waves, and drop- (decrement-) waves. Simultaneous stage-time graphs at four points, recorded on a chronograph, accompany the report.--John B. Drisko

John B. DRISKO, Wave motion in a channel, Amer. Geophys. Union Trans., p. 516, 1933.

This paper discusses briefly the nature of power-waves (abrupt increase of flow in a channel), mentions their relation to solitary waves of translation, and describes experimental work on various wave-types done in a small channel. The experimental work provided substantiation of J. Scott Russell's work with solitary waves, showed something of the nature of tidal waves propagated into a canal, and of the behaviour of power-waves.--John B. Drisko

L. DUBREIL-JACOTIN, Waves of permanent type in heterogeneous liquids, Accad. Lincei, Atti, v. 15, pp. 814-819, May 15, 1932 (in French) [see Abs. No. 3529, Sci. Abs. A., v. 35, 1932].

Confining his attention to the two dimensional case when the motion is the same in parallel vertical plane, the author establishes rigorously certain properties of waves in heterogeneous liquids.--Calif.

M. L. DUBREIL-JACOTIN, Rigorous determination of permanent periodic waves of finite amplitude, C.-R., v. 197, pp. 818-821, October 16, 1933 (C.-R. Hebdomadaires des Seances de l'Academie).

A rigorous solution of the propagation in a vertical plane of two-dimensional waves in a fluid of infinite depth is discussed. The solution indicates the existence of an infinity of waves comprising as particular cases those discussed by Gerstner and by Levi-Civita.--Calif.

M. L. DUBREIL-JACOTIN, Two-dimensional periodic waves in heterogeneous liquids, C.-R., v. 200, pp. 210-212, January 14, 1935.

The rigorous study of the constant periodic waves in heterogeneous incompressible fluids is undertaken. The case in which the diffusion is negligible is considered, especially in the particular instance important for further application, when the distribution of the density is exponential.--Calif.

M. L. DUBREIL-JACOTIN, Waves of permanent type in heterogeneous liquids, Accad. Lincei, Atti, v. 21, pp. 344-346, March 3, 1935.

In a previous note [see abstract 3529, 1932] it was shown that it is impossible to propagate a barotropic wave, that is, one for which the lines of constant pressure and density coincide with the lines of flow, in a heterogeneous liquid of finite depth, and that Gerstner waves were possible solutions in the case of infinite depth. It is here shown that the Gerstner waves is the only possible barotropic solution.--Calif.

Gilbert H. DUNSTAN, The moving hydraulic jump, M.S. thesis, Univ. of Iowa, 28 pp., August 1929.

The theory of the hydraulic jump is developed for the general case in which the position of the jump moves upstream or downstream. The general formulas are briefly discussed and simplified for the ordinary case of the stationary jump. The energy lost in the jump is considered, and the expression representing this loss is found to be the same for both the stationary and moving jump. Experiments checked the theoretical values quite well, a somewhat better check being obtained when the jump was moving upstream than when it was moving downstream. In addition to these experiments in the laboratory, a few measurements were made in the surf on the Coast of the Gulf of Mexico in an effort to prove that breakers are a form of jump. Sufficient data were not obtained to lead to definite conclusions. Bibliography has four entries.--G. H. Dunstan

I. V. EGUIAZAROV, Analysis of pondage conditions at the Volhov Hydroelectric Plant, Sci. Res. Inst. Hydrotechnics Trans., Leningrad, v. 12, pp. 5-23, 1934.

Mathematical analysis of observations on upstream propagation of wave in Volhov River due to shutdown of plant (in Russian, with brief abstract in English, pp. 21-23).

I. V. EGUIAZAROV, Regulation of the water level in the reaches of canalized rivers and regulation of the flow below the last lock-dam according to whether the water power is used or not, 16th Internat. Cong. Navigation, Brussels, 1935, 1st Section, 2nd Question (in English).

National Hydraulic Laboratory has a copy.--H.N.E.

I. V. EGUIAZAROV, Unsteady wave motion in long pools, Sci. Res. Inst. Hydrotechnics Trans., Leningrad, v. 16, 1935 (in Russian with English summary).

National Hydraulic Laboratory has a copy.--H.N.E.

I. V. EGUIAZAROV, Investigation of wave motion in long pools, Sci. Res. Inst. Hydrotechnics, Leningrad, v. 19, pp. 105-135, 1936 (in Russian with English summary).

National Hydraulic Laboratory has a copy.--H.N.E.

G. EVANGELISTI, Hydraulic problems treated by symbolic calculations, Elettrotecnica, v. 22, pp. 134-141, February 25, 1935.

A method of investigation is explained based on the employment of functional operators, with which can be treated the phenomena of propagation of hydrodynamic perturbations reducible to the equations of vibrating cords. Examples of practical interest are given which can be dealt with by this method in a relatively simple way compared with the usual means employed.--Calif.

W. FENCHEL, Canal waves of permanent type, Accad. Lincei, Atti, v. 13, pp. 740-743, May 17, 1931.

"Wave-motion in a canal is of permanent type if the free surface seems to move along the canal with a constant velocity without change of form. A simplication of the conclusions in Levi-Civita's paper on progressive waves of permanent type" [ibid. ser. 5, 16 pp. 777-790, 1907].

D. FISON, Manner of flow of river in flood, J. Inst. Eng. Australia, v. 8, No. 5, pp. 161-169, May, 1936.

Further discussion of speed of increments of rate of discharge of rivers; rating curves at average cross-sections; variable flow in stream; temporary storage; method of delineating flood-flow (see also Eng. Index 1935, p. 476).--Calif.

FLAMANT, Hydraulique, 2nd edition, p. 415, 1900.

Theoretical study on waves produced by moving a plate horizontally in a rectangular channel. --H. C. Lay

The flow of streams, The Engineer, v. 58, p. 294, October 17, 1884.

Article summarizes notes by George Maw which were sent to "Nature" by J. D. G. Smith. A mountain stream falling into the Lake of Thun near Merligen has a straight paved channel 15 feet wide with a slope 1 in 12 at the lower end and 1 in 9 at the upper end. Water flowing in this channel moves in a ladder of low advancing waves occurring at intervals of about 40 feet on the flatter slope and about 12 feet on the steeper slope. In the former, a floating body travels at a rate of 9.5 feet per sec while the wave-heads advance at a rate of 13 feet per sec and the intervening reaches of stiller water at about six feet per sec. On the steeper slopes a floating body travels at the rate of 12.5 feet per sec. Variations of velocity in a vertical section with a maximum below the water-surface is said to explain the observation that men navigating barges down the Severn River are able to steer with a moderate degree of effectiveness.--F.T.M.

J. R. FREEMAN, Flood problems in China, Trans. Amer. Soc. Civ. Eng., v. 85, pp. 1405-1460, 1922.

Flood-waves are discussed briefly on pages 1459-1460.

P. FROSINI, Studio idrologico del bacino del Tevere, Annali dei Lavori Pubblici, v. 70, No. 6, pp. 492-525, June, 1932.

Hydrological study of Tiber River watershed; rainfall and runoff record; floods; rate of rise of flood-levels in river.--Calif.

A. L. GALBRAITH, The flood on the Latrobe River, Victoria, Australia in December, 1934, Inst. Eng. Australia, v. 7, pp. 377-386 [see Civ. Eng. Abs., v. 67, pp. 180-181, April 1936].

Describes the flood, increases in river-velocity, etc., and the effects upon the Yallourn Power-Station.--Calif.

A. GAY, Permanent waves in a circular canal of arbitrary section, C.-R., v. 196, pp. 1462-1464, May 15, 1935.

Supplementing work by Levi-Civita and by Geppert, the author discusses wave-propagation in a fluid contained in a circular channel of arbitrary cross-section.--Calif.

A. H. GIBSON, Tidal and river models, J. Inst. Civ. Eng., supp. to No. 8, 1935-36, pp. 699-772, October, 1936.

Construction and operation of tidal and river models.--Calif.

E. C. GREAVES, Wave demonstration apparatus, Proc. Leeds Phil. Lit. Soc., v. 3, pp. 18-19, January, 1935.

A novel lecture-demonstration apparatus for showing surface-water ripples is described. The illuminating stroboscopic disk carries a rotor which itself provides the alternating-current for energizing the water-dipper so that whatever wave-length ripples are produced they are always in correct stroboscopic view.--Calif.

G. GREEN, On the motion of waves in a variable canal of small depth and width, Trans. Cambridge Phil. Soc., v. 6, 1837, Math. papers, London, 1871, pp. 223-230 [see also Note on the motion of waves in canals, Ibid., pp. 271-280, Trans. Cambridge Phil. Soc., 1839.]--R.E.H.

Nathan C. GROVER, Standing waves in rivers, Trans. Amer. Soc. Civ. Eng., v. 85, pp. 1400-1404, 1922.

Explanation of standing flood-waves moving in a stream, by considering the bottom friction as the essential cause.--H. C. Lay

C. E. GRUNSKY, Discussion on "The flood of March, 1907 in the Sacramento and San Joaquin River Basins, California"(W. B. Clapp), Trans. Amer. Soc. Civ. Eng., v. 61, pp. 331-345, 1908.

General discussion of flood-wave phenomena. Graphical method of finding the maximum discharge at a downstream station from the mass-curve of discharge at an upstream station.--H. C. Lay

R. F. GWYTHER, The classes of progressive long waves, Phil. Mag. (5), L. Lond., pp. 213-216, 1900; see supp. paper, ibid., pp. 349-352.--R.E.H.

H. B. HACHEY, Probable effect of tidal power development on the Bay of Fundy tides, J. Frank. Inst., v. 217, pp. 747-756, June, 1934 [see Sci. Abs., 1337, p. 487, 1934].

The tidal phenomenon of the Bay of Fundy is of the stationary wave-type, and this combined with a progressive wave is responsible for the very large tides there. The stationary wave-oscillations of the Bay of Fundy are not transmitted to Passamaquoddy Bay, etc.--Calif.

E. T. HANSON, The theory of ship waves, Proc. R. Soc. London, A, v. 3, pp. 491-529, 1926.

The problem is discussed mathematically using theory of complex variables. One problem discussed deals with the wave-formation due to a ship moving in the upper surface of two fluids of different density which are superposed upon one another with, in the undisturbed state, a horizontal surface of separation.--F.T.M.

A. W. HARRINGTON, Rainfall and stream-flow conditions during floods in Central and Southern New York, J. Amer. Water Works Ass., v. 28, pp. 1-5, 1936 [see Civ. Eng. Abs., v. 68, p. 118].

Description of the flood which occurred July 7 and 8, 1935; magnitude of rainfall, flood-flows, and damage done.

HEGLY, Sur la propagation d'une onde solitaire dans un canal reduit, a section trapezoidale (Propagation of a solitary wave in a reduced channel of trapezoidal section), C.-R., v. 199, pp. 826-828, October 29, 1934 [see also abstracts, v. 30, pl. 129].

The propagation of a solitary wave in a model consisting of a lock connecting two reaches is investigated experimentally, after the manner of the experimental work of Russell.--Calif.

K. HIDAKA, Seiches in a channel, Imp. Marine Obs., Kobe, Japan, Mem. 5, pp. 327-358, March, 1935 (in English), Memoirs Imp. M. Obs. [see Sci. Abs. A, v. 38, p. 708, 1935].

Reference is made to the theory developed for land-locked basins and those in a gulf or bay in earlier publications. In the paper the possibility of seiches being generated in a channel communicating on both sides with the open sea is demonstrated on theoretical grounds.--Calif.

W. H. HOLMES, Traveling waves in steep channels, Civ. Eng., v. 6, p. 467, 1936.

Robert E. HORTON, Channel waves subject chiefly to momentum control, U. S. Dept. Agric., SCS-TP-16 (mimeog.), 51 pp., May, 1938. (See page 606 for abstract and references to other pertinent articles by Doctor Horton.)

A. T. IPPEN and R. T. Knapp, A study of high-velocity flow in curved channels, Amer. Geophys. Union Trans., 1936.

Experiments on waves due to high-velocity flow in curved channels with different conditions of the bed-slopes.--H. C. Lay

C. S. JARVIS, Flood flow characteristics, Trans. Amer. Soc. Civ. Eng., v. 89, pp. 985-1032, discussion, pp. 1033-1104, 1926.

Maximum observed flood-discharge rates are tabulated for nearly 1000 floods on streams in the United States, and approximately 40 on streams in foreign countries. Record flood-flows in sec-feet per square mile are plotted as functions of the corresponding drainage-area and runoff-formulas of the Myers' type are suggested. (Maximum rate of flood-discharge varies as square root of drainage-basin area.) Some 20 runoff-formulas which depend upon the drainage-area are compared graphically. The paper and discussions do not treat flood-waves directly.--F.T.M.

C. S. JARVIS and others, Floods in United States, magnitude and frequency, U. S. Geol. Sur. Water-Supply Paper No. 771, 497 pp., 3 supp. sheets, 1936 [see Eng. Index, pp. 454-455, 1935].

Methods for estimating floods; examples of procedures for analyzing flood-flows; momentary flood-peaks, and other flow-characteristics of flood-rises. Bibliography relating to flood-flow, etc.--Calif.

Harold JEFFREYS, On water waves near the shore, Phil. Mag., Ser. 6, v. 48, pp. 44-48, 1924.

Waves in deep water are essentially a three-dimensional phenomenon. This appears to be consistent with the hypothesis that such waves are due to turbulence in the wind. G. I. Taylor has shown that the mean-square deviation of the velocity in any direction from its mean value is the same whether the direction be along the wind, across it, or vertical, and that gusts in any direction last about the same time. Near the shore, however, the crests run together transversely and form a series of waves with very long crests approximately parallel to the shore which then approach the shore and break one by one. The article gives a brief mathematical treatment of the latter type of wave.--F.T.M.

Harold JEFFREYS, The flow of water in an inclined channel of rectangular section, Phil. Mag. (6), Ser. 5, v. 49, pp. 803-807, 1925.--H. C. Lay

R. D. JOHNSON, Surges in an open channel, Trans. Amer. Soc. Civ. Eng., v. 81, pp. 112-115, 1917, discussion, pp. 116-124.

Equations for the height and velocity of a surge in a smooth rectangular channel are shown to correspond to equations of the moving hydraulic jump.--F.T.M.

Raymond D. JOHNSON, The correlation of momentum and energy changes in steady flow with varying velocity and the application of the former to problems of unsteady flow or surges in open channels, Engineers and Engineering, v. 39, pp. 233-240, 1922.

The difference between the laws of conservation of energy and momentum is pointed out. Pressure-waves and suction-waves are discussed--the former as standing waves set in motion relative to the Earth. The suction-wave has no counterpart in a standing wave and moves with constantly changing profile--the top of the wave moving more rapidly than the bottom with continual lengthening of the wave-front. By dividing the canal into short frictionless sections with a tiny drop in water-level at the end of each section, P. Wahlman showed that the wave-behavior can be analyzed without significant error, it is stated. Wahlman's method is illustrated by an example.--F.T.M.

KAMINSKY, Die Überschwemmung in Leningrad am 23 Sept. 1924, Nach. Zentr. Bur. Hydromet. Leningrad, Heft 4, 19 pp. (Russian, with German abstract).--R.E.H.

F. KARTENBECK, Aehnlichkeitsbedingungen bei Stroemungsvorgangen und ihre Ueberpruefung durch Modellversuche, Bauingenieur 17, v. 7/8, pp. 55-60, February 21, 1936.

Principle of similitude and its application to testing of hydraulic model--considering the case of turbulent flow and wave-motion.--Calif.

Karl F. KEELER, Flow of the Rio Grande and tributary contributions, Water Bull. No. 6, Internat. Boundary Comm., United States and Mexico, Dept. State, U.S.A., pp. 79-94, 1936.

Contains data and diagrams relative to rate of travel of flood-crests between different points on Rio Grande River. Most of the basic data from which these diagrams were prepared are given in a publication entitled "Special flood report (mimeograph), Flood of September and October 1932, International portion of the Rio Grande, American Section," International Boundary Commission, United States and Mexico, Dept. State, U.S.A., 1933.--R.E.H.

Karl R. KENNISON, The hydraulic jump in open-channel flow at high velocity, Trans. Amer. Soc. Civ. Eng., v. 80, pp. 338-353, 1916, discussion pp. 354-420.

This paper opens for discussion, apparently for the first time in American literature, the analysis of the hydraulic jump in rectangular channels. In the discussion the theory of the hydraulic jump is based on the conservation of impulse and momentum and reference is made to previous foreign studies.--F.T.M.

Horace W. KING, Translatory waves in open channels, Civ. Eng., v. 3, pp. 319-321, June, 1933.

In general when the discharge in a channel is suddenly changed a positive or negative accelerating wave is formed. If the change acts to increase the depth, the wave has an abrupt face and if it acts to decrease the depth, the wave has a sloping face. A number of formulas for practical application are given. Channel-friction has a modifying effect on the height and velocity of a wave and the profile of the water-surface behind it. In deep water for waves of moderate height the velocity of wave varies approximately as the square root of the maximum depth of flow and can often be determined closely enough by neglecting channel-friction. The principles involved in computing the water-profile back of a wave by analysis of short reaches are comparatively simple, it is stated, but the computations may be long and tedious.--F.T.M.

R. Z. KIRKPATRICK and H. G. Cornthwaite, Surges in Gaillard Cut from lockages at Pedro Miguel, Panama Canal, Mil. Eng., v. 12, pp. 86-87, January-February, 1920.

M. KLEITZ, Notes sur la theorie de mouvement non permanent des liquides et sur son application a la propagation des crues des rivieres, Annal. Ponts et Chaussees, 2$^e$ Semestre, pp. 133-196, 1877.--H. C. Lay

K. KOENUMA, Effect of steady wind on the surface level of a canal, Imp. Marine Obs., Kobe, Japan, Mem. v. 5, pp. 359-372, March, 1935 (in English) [see Sci. Abs., A, v. 38, p. 708, 1935].

The effect of a steady wind on the surface-level of an infinitely long canal whose coasts are parallel to one another is examined theoretically.--Calif.

D. J. KORTEWEG and G. DeVries, On the change of form of long waves advancing in a rectangular channel, and on a new type of long stationary waves, Phil. Mag., Ser. 5, v. 39, pp. 422-443, 1895.

According to Lamb and Basset, long waves in a rectangular canal must necessarily change their shape as they advance, becoming steeper in front and less steep behind, even when friction is neglected. Since the investigations of Boussinesq, Lord Rayleigh, and St. Venant on the solitary waves, there has been some cause to doubt the truth of this assertion. The authors conclude from "somewhat tedious calculations" that in a frictionless liquid there may exist absolutely stationary waves and the form of their surface and the motion of the liquid below it may be expressed by means of rapidly convergent series. Considering one of the two systems of waves starting in opposite directions in consequence of any disturbance after their complete separation from each other, the authors develop a new type of wave which in analogy with sinusoidal waves they have called cnoidal waves. The mathematics include an analogy of stationary waves, stationary periodic waves (cnoidal waves) definition of non-stationary waves, and surface-profiles.--F.T.M.

K. KURIHARA, Transmissibility of long waves along a canal with abrupt changes in depth, Imp. Acad., Tokyo, Proc. v. 11, pp. 316-318, October, 1935 (in English) [see Sci. Abs., A., v. 39, p. 99, 1935].

The problem of a water-wave which is partly reflected and partly transmitted at a point where there is an abrupt change in the section of the canal is extended to the case when there are two such points, so that the portion of the canal between them is shallower or deeper than other portions.--Calif.

B. LACAZE, Une crue artificielle sur l'Aar, Revue Industrielle, v. 65, No. 2309, pp. 161-171, Paris, April, 1935.

Report on artificial flood-wave produced on Aar River, Switzerland, on February 6, 1920, based on report by K. Kobelt, published by Service Federal des Eaux, Switzerland; observations on progress of wave; bearing of observations on effect of pumped storage released into River.--Calif.

Horace LAMB, Hydrodynamics, 4th Ed., 1916.

E. W. LANE, Recent studies on flow conditions in steep chutes, Eng. News-Rec., v. 116, p. 5, January 2, 1936.

This article is based on observations on the flow in an irrigation-chute and discusses the changes which take place in the flow-conditions as the water progresses down this structure. The action at vertical curves and the waves set up in a channel of non-uniform width are also treated. Data are also given on the friction-losses of flow at high velocities. Comparisons are made between the observed and computed hydraulic position of the hydraulic jump.--E. W. Lane

E. W. LANE and O. J. Baldwin, Flush wave velocities in sewers, Eng. News.-Rec., v. 116, pp. 848-849, June 11, 1936.

Describes the results of experiments on waves produced by flush-tanks in sewers with very flat gradients, including diagrams showing the formation of the wave-front and the velocity of movement. Shows why the wave-front moves faster than the velocity of the water forming the wave.--E. W. Lane

E. W. LANE, Predicting stages for the lower Mississippi, Civ. Eng., v. 7, pp. 122-125, February, 1937.

This article gives a method of predicting stages on the lower Mississippi based on the stage-relation method. It describes the method used for stages between which there are no important tributaries entering the stream and also the case where important tributaries join. It shows the result of the application of the methods to previous floods and the method by which the lowering due to crevasses in past floods can be computed. Data are also given on the time of travel for flood-peaks of various heights.--E. W. Lane

Ernest LATHAM, Waves--their formation, action, and effect on marine works, Engineering and Contracting, v. 57, pp. 310-312, March 29, 1922.

Digest of paper in Water and Water Engineering, London, not directly applicable to flood-waves.

Harald LAUFFER, Energie und Fliesszustand in Gerinnen mit Grossem Gefälle (Energy, and state of flow in steep channels), Wasserkraft und Wasserwirtschaft, v. 30, pp. 78-82, 1935.

For conditions of flow at neutral depth, the author shows mathematically and experimentally that the pressure-head in the interior of a liquid is substantially less than its perpendicular distance from the liquid surface in steep channels. Thus the q-line is dependent on the slope as is also the pressure plus momentum. The elevation of the water-surface corresponding to minimum pressure plus momentum is the critical zone between streaming and shooting flow and simultaneously is stage of maximum discharge. Depending on the state of flow, Froude's number may range between limits of 0 and 1. Bibliography includes:

P. Böss, Berechnung der Wasserspiegellage, Forschungsarbeiten des V. D. I., Heft 283, 1927.
F. Engel, Non-uniform flow of water, The Engineer, v. 155, p. 392, 1932.
F. Engel, Wassermessungen mit offenen, seitlich eingeschnürten Kanälen (Venturikanäle) Z.d.V.D.I., v. 77, p. 1285, 1933.
R. Ehrenberger, Versuche über die Verteilung der Drücke an Wehrrücken infolge des abstürzenden Wassers, Die Wasserwirtschaft, Wien, v. 22, Heft 5, 1929.
Koch-Carstanjen, Bewegung des Wassers und dabei auftretende Kräfte, J. Springer, 1926.
J. Kozeny, Ueber die gleichförmige Bewegung des Wassers in elementarer Darstellung, Die Wasserwirtschaft, Wien, v. 22, p. 500, 1929.
Th. Rehbock, Abfluss, Stau und Walzenbildung, J. Springer, 1917.
H. Rouse, Verteilung der hydraulischen Energie Bei Einem lotrechten Absturz, R. Oldenbourg, 1933.
K. Safranez, Wechselsprung und die Energievernichtung des Wassers, Der Bauingenieur, v. 8, p. 898, 1927.
H. Schwarzmann, Die Abflusserscheinungen und Druckverhältnisse an Klappenwehren, R. Oldenbourg, 1934.--F.T.M.

Hung-Chi LAY, A digest of the English literature of flood waves, M.S. thesis, Univ. of Iowa, 158 pp., June, 1938.

Approximately 70 papers in the English literature of flood-waves are reviewed and correlated. Bibliography contains 69 entries.--F.T.M.

LECHALAS, Théorie général des réservoirs d'emmagasinement des crues, from "Hydraulique Fluviale," p. 434, Paris, Baudry et Cie, 1884.

The Dayton-Morgan Engineering Company has a translation of this article, prepared by K. C. Grant [see Trans. Amer. Soc. Civ. Eng., v. 93, p. 741, 1929].

Arthur R. LIDDELL, Wave proportions and their effects, The Engineer, v. 121, p. 474, June 9, 1916.

Applies only to waves of the sea.

Ping-Yi LIN, Prediction of floods, M.S. thesis, Univ. of Iowa, 202 pp., January, 1926.

On the hypothesis that flood-prediction is the most economical means of flood-protection, the author considers the flood-problem from several angles. Chapter I deals with the propagation of flood-waves on rivers and presents mathematical derivations of formulas for determining the rate of propagation of flood-waves, for computing the velocity of flood-wave, and for predicting the height of the wave. Chapter II develops equations for the profile and volume of a roll-wave and a translatory wave. Chapter III deals with actual floods, principally the floods of 1924 at

Iowa City. Although some of the physical data were assumed, reasonably close estimates of the time of arrival of the crest were made using the formulas of Chapter I. Chapter IV contains a general discussion of the hydrologic factors affecting floods, quotations from other authors on flood-discharge and frequency, and a theoretical flood-hydrograph which is symmetrical about the peak-ordinate. A number of interesting pictures of the floods of 1924 are included. Bibliography contains 25 entries.--J. W. Howe

G. Puls LOUIS, Construction of flood flow routing curve, House Doc. 185, 70th Cong., 1st Session, Report on partial survey for Tennessee and tributaries, Appen. B, Part II, pp. 46-52, 1928.--H. C. Lay

M. Edmond MAILLET, Sur les Procédés d'Annonces des Crues Fondés en Théorie (Methods of flood prediction based on theory), Annal. Ponts et Chaussées, v. 92, T1, pp. 145-156, 1922.

This is a review of a number of theoretical methods for predicting flood-waves, giving in each case the original reference and a summary of the method. The best flood-predictions are obtained by making a theoretical study of available stage-discharge records rather than proceeding purely empirically. Previous references describing the author's methods are: Boussinesq, Essais; Kleitz, Annales; Maillet, J.E.P. 6 or 8; Maillet, Congrès, S.P. (1) Case of two stations without intermediate tributaries. (2) Case of a downstream station dependent upon several upstream stations: (a) Law of increments, linear functions of depth; (b) law of Breuillé, curvilinear functions [Annal. Ponts et Chaussées, August, 1896, p. 128]; (c) other laws and graphical methods; (d) method of Allard [Flamant, Hydr., p. 414]. (3) Aside from the method of comparison, all the above methods are theoretically equivalent to a first approximation. This does not distinguish the maximum values from other values. Practically, the conditions differ from those assumed in that the constants actually vary somewhat. The type of observations available affects the type of theory adapted for the prediction. (4) Method of comparison; base the prediction of flood-waves on one river from comparative results upon another; limits of comparison may be applied mathematically [Boussinesq, Kleitz, Flamant, Hydr., p. 386; Maillet, Annal. Ponts et Chaussées, v. 3, pp. 294, 308, and 326, 1919]: (a) Duration of propagation, effect of neglected tributaries important on duration; (b) types of flood-waves must be carefully distinguished in making these comparisons, particularly floods with broad waves and floods in which the maximum discharge lowers in propagation, also the effect of two closely consecutive flood-waves with an intervening minimum discharge.--Chilton A. Wright.

Francesco MARZOLO, Bacini a Marea e Foci Langunari (Tidal basins and broad, shallow inlets), L'Energia Elettrica, v. 12, December, 1935.

National Hydraulic Laboratory has a copy.--H.N.E.

M. P. MASSE, L'Amortissement des Intumescences (Damping of waves), Rev. Gén. l'Hydraulique, v. 1, No. 6, pp. 300-308, November-December, 1935.--H.N.E.

Ludwig MATTHIESSEN, Experimentelle Untersuchungen ueber das Thomson'sche Gesetz der Wellenbewegung auf Fluessigkeiten unter der Wirkung der Schwere und Cohaesion. Ann. Physik und Chemie, v. 38, pp. 118-130, 1889.

Author presents data from the laboratory on capillary waves in mercury, distilled water, absolute alcohol, sulfuric ether, and carbon disulfide. He concludes that Thomson's formula for capillary-waves velocity, $v^2 = (\lambda/2\pi)g + (2\pi/\lambda)t$ and $v^2 = 981.4[(\lambda/2\pi) + 0.074(2\pi/\lambda)]$, in which $g$ = acceleration of gravity, $t$ = surface-tension of the liquid, and $\lambda$ = wave-length, is very precise and deviates only 0.5 mm in the neighborhood of the critical point for average wave-lengths of 13 mm and minimum velocities of 20 cm per sec.--F.T.M.

W. J. McALPINE, Waves of translation in fresh water, Trans. Amer. Soc. Civ. Eng., v. 1, pp. 333-343, 1872.

Investigation of a dam-failure case (on Black River, New York, April 21, 1869) with explanation of the damage due to wave-propagation downstream by applying Russell's principle of wave of translation. Experiments on flood-waves to illustrate the dam-failure phenomena using a wooden flume eight feet long, six inches wide, and one foot high.--H. C. Lay

W. N. McCLEAN, Flow of River Dee, Water and Water Eng., v. 36, No. 440, pp. 602-606, discussion pp. 606-608, November, 1934.

Correlation of water-levels and river-flows; flood-flows.--Calif.

J. McCOWAN, On the highest wave of permanent type, Phil. Mag. (5), v. 38, pp. 351-358, 1894.

J. McCOWAN, On the solitary waves, Phil. Mag., Series 5, v. 32, pp. 45-58, 1891; note supplementary to a paper On the solitary waves, ibid., pp. 553-555.

Based on his experiments outlined in his report on waves to the British Association in 1844, Scott Russell concluded that the solitary wave was unique and has a definite form depending only on the depth and the volume of the water composing it. This form, in the case of a wave of elevation, appeared to be propagated with constant velocity and without any change except such degradation in height as might reasonably be attributed to frictional and other disturbances. The solitary wave is included in the general theory of long waves only to a very rough approximation, for its velocity does not agree closely with that of the long waves nor does it gradually increase in steepness in front, as the long wave does. The change which does take place in it is simply a diminution in height and consequent increase in length such as might be caused by a dissipation of its energy by friction, etc. In this paper the author discusses briefly the general theory of the solitary wave and examines cases in detail, mathematically, after introducing a simple but close approximation. Analytical conclusions are essentially in agreement with Scott Russell's experiments and confirm his opinion as to the unique character of the solitary wave of elevation. The mathematical approach involves functions of complex variables. Other topics discussed in the paper include the surface-pressure in the approximate theory of the author; the approximations of Boussinesq and Lord Rayleigh; the length, volume, and displacement of the waves; the motion and paths of the particles; the energy of the wave, its limiting height; and approximate theory of breakers.--F.T.M.

Mansfield MERRIMAN, Treatise on hydraulics, ninth Ed., pp. 351-352, John Wiley and Sons, 1914.

In the Johnstown (Fennsylvania) Flood of 1889 a vertical wall of water variously estimated at from 10 to 30 feet in height moved down the Valley carrying on its front brush and logs mingled with spray. In 41 minutes it traveled a distance of 13 miles down the descent of 380 feet, and the average velocity was about 28 feet per sec. Roughness of surface is an essential condition for the formation of the bore in a steep valley.--F.T.M.

Carroll F. MERRIAM, Time passage of flood peaks, M.S. thesis, March, 1936.

Gives an inflow form of diagram, with explanatory matter, showing time of travel of flood-crests between different points on Susquehanna River and tributaries in flood of March, 1936.--R.E.H.

MARINE Observer's Handbook, Met. Office, London, 2nd Ed., pp. 69-76, 1918.--R.E.H.

J. H. MICHELL, The highest waves in water, Phil. Mag., Ser. 5, v. 36, pp. 430-437, 1893.

Introducing functions of complex variables, the author investigates, as a two-dimensional problem, the ocean-waves which advance without change in form. Details are presented leading to depths and velocities of waves in deep water and similar solutions are suggested for waves in water of finite depth.--F.T.M.

Elmer E. MOOTS, A study in flood waves, Ph.D. thesis, 115 pp., February, 1927; see also: A study in flood waves, by Elmer E. Moots, Bull. 14, Univ. Iowa Studies in Engineering, 24 pp., 1938; A study in the theory of flood-waves, by Elmer E. Moots, Amer. Geophys. Union Trans., Part I, pp. 383-386, 1938.

The hydromechanic equations governing a simple flood-wave in a wide rectangular channel are developed and discussed. Emphasis throughout is placed on a simplication of the notation commonly used in hydromechanics. The profile of the roll-wave and the profile of the monoclinal or rising flood-wave, after equilibrium has been established, is obtained in terms of elementary functions from general hydrodynamic equations. The velocity of each of these waves is obtained from Kleitz's equation for the velocity of a constant flow. It is found experimentally that there exists a close correlation between the maximum velocity of a flood-wave of given height and the velocity of Russell's wave of translation of the same height, the latter as modified by Bazin when projecting it against the current on running water.--Elmer E. Moots

M. A. MOSTKOV, Graphical hydraulics of variable flow, Sci. Res. Inst. Hydrotechnics Trans., v. 9, pp. 51-79, 1933 (in Russian); L. G. Straub has translation.

Floyd A. NAGLER, Certain flood-flow phenomena of Iowa rivers, Amer. Geophys. Union Trans., 1932, pp. 322-327.

An isolated rainstorm on August 1-2, 1929, centered on the long narrow watershed of the Iowa River, 70 miles above Iowa City, with an eight-inch fall in about four hours near the storm-center. At Iowa City where the drainage-area is 3230 square miles, a double-peaked hydrograph resulted from a single-peak of rainfall and a sharp break in the falling flood-hydrograph was accompanied by an increase in the rate of flow-depletion. The first peak was ascribed to rapid runoff from nearby hilly country and to limited channel-storage. The second peak which occurred five days later was characteristic of flow retarded by storage. The break in the receding hydrograph occurred when the River fell to bank-full stage. At Marshalltown where the drainage-area is 1500 square miles, the peak flood-discharge exceeded that at Iowa City. Runoff-percentages for typical Iowa summer floods are given.--F.T.M.

Wilhelm MEYER, Die Flutbrandung des Tschien-Tang-Kiang bei Haining (The tidal bore of the Tschien-Tang-Kiang at Haining), Wasserwirtschaft und Technik, v. 2, No. 28, pp. 361-363, 1935.

At Kanpu, on the left bank of Hangchow Bay, 30 km below Haining and 70 km below Hangchow, the depth of the Bay diminishes from seven to nine meters to one to one and a half meters (proceeding upstream). Spring tides impressed upon the funnel-shaped Bay first appear as choppy waves below Kanpu and rise to approximately 3.5 meters two hours after low tide. About one and a half hours later the bore can be heard at Haining and two and a half hours later it appears as a wall of water two km long, 2.5 to 5.5 meters high, moving at a speed of 20 to 25 km per hour with turbulent face sloping 40° to 70°. Height, speed, and appearance are maintained about 30 km above Haining. The bore is 1.8 to 2.1 meters high at Hangchow and disappears a short distance upstream, although tides are apparent 40 km above Hangchow. Duration of flood-tide is three hours at Haining and one and a quarter hours at Hangchow. Neap tides at Haining are only 0.60 to 0.90 meter in calm weather.--F.T.M.

William Barclay PARSONS, The Cape Cod Canal, Trans. Amer. Soc. Civ. Eng., v. 82, pp. 1-143, 1918, discussion pp. 144-157.

The canal is the largest open artificial waterway connecting two seas having non-synchronous tides. Part 1 is devoted to history and location, and part 2 is devoted entirely to hydraulics. Hydrographic data pertinent to the canal are summarized, and the problems of wave-propagation are analyzed mathematically. The author concludes that the Airy-Levy formula derived by harmonic analysis with a modification proposed by the author, represents the only rational method for solving the hydrodynamic problems arising within a tidal canal. It is questionable, he adds, whether in practice the refinement and complicated numerical work connected with the harmonic analysis are justifiable; and approximate methods, outlined in the paper, are recommended for evaluation of the velocities in canals subjected to tidal influences.--F.T.M.

R. S. PATTON and H. A. Marmer, The waves of the sea, Nation. Res. Council, Bull. No. 85, Physics of the Earth, v. 5, Oceanography, pp. 207-208, 1932.

The subject is treated under the following headings: Wave-movement; measurement of waves; relation of waves to wind; the swell; the calming of waves; waves in shallow water; the wave of translation; wave-energy; seismic waves; seiches. Bibliography contains 38 entries.--F.T.M.

C. R. PETTIS, Relation of rainfall to flood runoff, Mil. Eng., v. 28, pp. 94-98, March-April, 1936.

One diagram of a composite flood-wave shows wave-velocities in terms of the average velocity of the entire cross-section at crest. This diagram shows that the average ratio of wave-velocity to average discharge-velocity at crest is 1.35. Much of the discussion is relative to the author's width formula for floods, originated in 1927 and published in Engineering News-Record, June 21, 1934.--F.T.M.

Chesley J. POSEY, Slide-rule for routing floods through storage reservoirs or lakes, Eng. News-Record, v. 114, pp. 580-581, April 25, 1935.

This method involves short uniform time-increments and requires a separate set of scales for each reservoir having a different volume-depth or outflow-depth relation. Lengths along slide and stock represent total volumes as "day-second-feet," the former bearing a single scale with graduations defined by $C = [S_2 + (1/2)o_2t]$, and the latter bearing two opposed scales with a common origin defined by $A = i\ t$ and $B = [S_1 - (1/2)o_1t]$, in which $i$ = average inflow rate, $t$ = length of step (time increment), $S_1$ and $S_2$ = storage at beginning and end of step, respectively, and $o_1$ and $o_2$ = outflow rates at beginning and end of step, respectively. The outflow rate is assumed to be a known function of the total-storage, and the storage-equation is of the form $(A + B) = C$. Given the inflow rate and the outflow rate at the beginning of a step, the outflow rate at the end of the step can be obtained directly by means of the slide-rule or by means of a nomograph illustrated.--F.T.M.

U. F. PROKOFIEVA and V. I. Novotorzev, Theoretical principles of designing transit stream flows (in Russian), Sci. Res. Inst. Hydrotechnics, Trans., v. 17, pp. 130-145, 1935.

The purpose of this paper is to present principal design formulas and practical applications of the theoretical method, proposed by N. M. Bernadsky, for the determination of pictures of flow. The method is based upon equations of longitudinal and transversal equilibrium of a stream

$$H_a - H_b = (V_b^2 - V_a^2)/2g + \int_{AB} [n^2V^2/h^{4/3}]\, ds$$

$$(H_c - H_d) = (1/g)\int_{AB} \sigma V^2 dn$$

The plotting of a so-called "orthogonal net" (flow-lines and lines normal to them) for a given current, by means of direct use of the above written equilibrium-equations, presents, however, considerable difficulties. The author has proposed, therefore, to use in practical applications, two working formulas, which he calls "the law of the net" and "the law of widening," respectively. These formulas are corollaries of the equilibrium-equations, mentioned above, and are as follows

$$k = k_o h' \left\{ \sqrt[5/3]{\ell' \, [(H_1 - H_2)/(H_{01} - H_{02})][(1 + \epsilon_o)/(1 + \epsilon)]} \; g[(n^2/h_c^{4/3}) - (I_s/V_c^2)] \, \ell \right\}$$

and $b = (h_o/h)b_o c$. In this paper practical methods are described for plotting transit-currents, flowing between solid banks, or between two zones of eddies.--Author's abstract

B. V. PROSKURIAKOV, Method of unsteady flow computations proposed by N. M. Bernadsky, as applied to flow caused by instantaneous destruction of dams (in Russian), Sci. Res. Inst. Hydrotechnics, Trans., v. 11, pp. 75-95, 1934.

This article contains an example of application of the method devised by N. M. Bernadsky for unsteady flow computations--to a particular case of flow, resulting from a break in a dam. In the first part of the article a general description of the method is given. The method consists in simultaneously solving graphically and by gradual approximations, of the equations of continuity and equilibrium. The equations have the following shape: $\partial Q/\partial x = b(\partial H/\partial t)$ and $FI = (v^2 b_c/C^2) + (F/g)(dv/dt')$, where b = width of the river at the given section; $(\partial H/\partial t)$ = change of elevation in a unit of time; $(\partial Q/\partial x)$ = change of discharge along a unit of length of the river; F = area of the cross-section; I = longitudinal slope; v = average velocity of flow in the cross-section; $b_c$ = average width of the channel; C = coefficient in Chézy's formula; g = acceleration of gravity; (dv/dt) = full differential of the velocity. At the same time, marginal conditions for the waves of upper and lower pools must be satisfied. These conditions are as follows: (1) Equation of the velocity of propagation of the upper-pool wave, $V v_b = \sqrt{gH}$; (2) equation of the velocity of propagation of the lower-pool wave, $v_H = 2\sqrt{gh}$; (3) condition of continuity, which requires that the discharge of water contained in the propagating wave should be equal to that passed through the terminal part. Constant equality of volumes of water in lower pool to those issuing from the upper pool, must be fulfilled when plotting of every instantaneous surface is being done. The procedure consists in plotting the instantaneous surfaces with subsequent checks (satisfaction of all above-mentioned conditions). In the second part of the article a practical example is given of an application of the method to a case of dam-failure. In the third part a comparison is made between instantaneous calculated levels and those measured in laboratory.--Author's abstract

PROPAGATION d'une Intumescence Allongée (Propagation of a long flood-wave), Rev. Gén. l'Hydraulique, v. 1, No. e, pp. 138-142, May-June, 1935.--H.N.E.

J. PROUDMAN, Tides in a channel, Phil. Mag., Ser. 6, v. 49, pp. 465-475, 1925.

Papers relate to the tidal dynamics of a channel whose section is uniform along its length but of varying depth from side to side. Author disagrees with Sir G. B. Airy's statement that "the ridge of waves cannot possibly stretch transversely to the channel" but adds that Airy's rule for the direction of rotation of tidal current is valid over wider conditions than Airy considered. The treatment is mathematical.--F.T.M.

V. PUPPINI, River flow and discharge from hydroelectric stations, Elettrotecnica, v. 20, pp. 505-510, August 5, 1933.

A particular case studied to illustrate the degree of decrease of amplitude of the wave as it travels down the river away from the plant. An equation is developed.--Calif.

W. J. M. RANKINE, Miscellaneous scientific papers, Griffin, London, 1881, pp. 481-494 and pp. 530-543.--R.E.H.

Lord RAYLEIGH, On progressive waves, London Math. Soc. Proc., v. 9, pp. 21-26, 1877.

A mathematical treatment not obviously applicable to flood-waves.--F.T.M.

Lord RAYLEIGH, Hydrodynamical notes, Phil. Mag., Ser. 6, v. 21, pp. 177-195, 1911.

Brief mathematical notes are presented on the following topics: Potential and kinetic energies of wave-motion; waves moving into shallower water; concentrated initial disturbance with inclusion of capillarity; periodic waves in deep water advancing without change of type; tide-races; rotational fluid-motion in a corner; steady motion in a corner of viscous fluid. In each of the analyses, the fluid is regarded as incompressible and the motion is assumed to take place in two dimensions. When there is no dispersion, the energy of a progressive wave of any form is half potential and half kinetic. Thus, in the case of a long wave in shallow water "if we suppose that initially the surface is displaced such that the particles have no velocity, we shall evidently obtain (as in the case of sound) two equal waves traveling in opposite directions whose total energies are equal, and together make up the potential energy of the original displacement. Now the elevation of the derived waves on behalf of that of the original displacement and, accordingly, the potential energy is less in the ratio of 4:1. Since therefore, the potential energy of each derived wave is one-quarter and the total energy one-half that of the original displacement, it follows that in the derived wave, the potential and kinetic energies are equal." [On waves, Phil. Mag., v. 1, p. 257, 1876; Scientific papers, v. 1, p. 254.]--F.T.M.

Sir John ROBINSON and John Scott Russell, Report of the Committee on Waves, 7th Rep. Brit. Ass. Adv. Sci., v. 6, pp. 417-496, 1837.

G. T. RUDE, Tides and their engineering aspects, Trans. Amer. Soc. Civ. Eng., v. 92, pp. 606-671, 1928.

Explanation of bore-phenomenon with mention of rivers in the world where bore occurs. Bore occurs in shallow rivers with broad flats, almost bare at low water.--H. C. Lay

John Scott RUSSELL, Report on waves, Rep. 14th Meeting Brit. Ass. Adv. Sci., pp. 311-390, 1844.

Paper discusses the solitary wave (wave of translation); experiments on positive and negative waves; characteristics of solitary waves; empirical formulas for velocity of wave-propagation, wave-length, wave-form, and range and path of motion of particular particles, etc.; complete classification of water-waves.--H. C. Lay

R. A. RYVES, Experiments with models of hydraulic works, Civ. Eng., London, v. 26, Nos. 315 and 316, pp. 44-46, September, 1932.

Review of progress in hydraulic-laboratory research with use of models in Europe and America; flow and waves in channels and rivers, etc.--Calif.

SAINT-VÉNANT, Démonstration élémentaire de la formule de propagation d'une onde ou d'une intumescence dans un canal prismatique, C.-R., v. 71, pp. 186-195.--R.E.H.

SAINT-VÉNANT, Théorie du mouvement non permanent des eaux, C.-R., v. 73 pp. 147-154, 237-240, 1871.--R.E.H.

SAINT-VÉNANT, Mouvement des molécules de l'onde dite solitaire, propagée à la surface de l'eaux d'un canal, C.-R., v. 101, pp. 1101-1105, 1445-1447, 1885.--R.E.H.

Thorndike SAVILLE, The 1929 flood in eastern North Carolina streams, Amer. Geophys. Union. Trans., 1932, pp. 361-370.

Gives data of flood-crest velocities on Cape Fear and Neuse rivers, North Carolina.--R.E.H.

A. SCHOKLITSCH, Ueber Dammbruchwellen (Waves below breached dams), Sitz.Ber. Kais. Akad. Wiss., Wien, v. 126 (2A), pp. 1489-1514, 1917.

Reference is made to earlier work by A. Ritter and Ph. Forchheimer (q.v.). Tests by A. Zeitlinger in small wooden channels substantially verified $U_s = -\sqrt{gH}$ for velocity of break in water-surface when gate retaining water to depth H in rectangular channel was suddenly removed. For small depths, H = 3.7 cm and observed velocities were 91 per cent of computed velocities. Tests by Schokolitsch on very smooth wooden channels 9.6 to 60 cm wide, 8 to 25 cm deep, and 26 meters in maximum length, and in open ditches 1.30 meters in maximum width, 1.0 meter deep, and 150 meters in maximum length indicated: (1) Roughness of reservoir has little effect on calculated discharge; (2) in a modification of Ritter's formula $U = \sqrt{g\,(d_1 + k\,q/U)}$ the coefficient k = 1.5 for wave with a smooth surface and k = 1.0 for a breaker; (3) water-surface at gate dropped to 0.50 H instead of 0.44 H (Ritter); (4) a rectangular reservoir L meters long and H meters deep is practically emptied after $(k'\,L/\sqrt{g\,H})$ sec if one side is suddenly removed (k' = 6 to 10). Other empirical formulas are based on tests of flow through rectangular slots and sluices.--F.T.M.

A. SCHOKLITSCH, Hydraulic structures, Eng. Ed., translated by S. Shulits; Flood-waves, pp. 63-65; Surges and waves in open channels, pp. 121-128.--H. C. Lay

Fred C. SCOBEY, Unusual flow phenomena, Civ. Eng., v. 1, pp. 1101-1103, September, 1931.

Brief illustrated discussion of hydraulic jump, stationary waves, over-running waves, curves, and air-entrainment.--F.T.M.

James A. SEDDON, River hydraulics, Trans. Amer. Soc. Civ. Eng., v. 43, pp. 179-229, 1900, discussion pp. 230-243.

Digest of Seddon's work was prepared by Robert E. Horton for the Committee on Flood Waves [see Amer. Geophys. Union Trans., 1938, pp. 374-382].

N. SEN, On the equation of long waves in canals of varying section, Phil. Mag., Ser. 6, v. 48, pp. 65-78, 1924.

Green [Mathematical papers, p. 225] was the earliest investigator of this subject and showed that in the case of progressive waves in a canal with slowly varying sections the elevation of water is inversely proportional to the square root of the breadth and to the fourth root of the average depth at the section. Soluble cases for different sections have been investigated by Chrystal [Some results in the mathematical theory of seiches, Proc. R. Soc., Edinburgh, v. 25, pp. 328, 1904] and J. Wedderburn [On long waves, Amer. J. Math., p. 211, 1914]. Some special solutions analogous to those corresponding to the motion of progressive waves are discussed in the article and the law of the variations of depth and breadth, for which such types of motion can exist, has been deduced.--F.T.M.

L. K. SHERMAN, Experiments on the effects of upper channel improvements upon the downstream flood heights, West. Soc. Eng. J., v. 28, No. 8, pp. 293-318, August, 1923.

Experiments on the effect of upper-channel improvements upon the downstream flood-heights, using a flume 7/8 inch wide, 66 feet long.--H. C. Lay

L. K. SHERMAN, Formula for wave velocity in open channels verified, Civ. Eng., p. 473, August, 1933.--H. C. Lay

L. K. SHERMAN, Illinois River flood, Eng. News, v. 75, pp. 550-551, March 23, 1916.

Low-water profile of 1901 and flood-profiles of 1844, 1904, and 1916 are shown from Grafton to Joliet. Travel of crest of flood of 1916 from Morris to Grafton is tabulated.--F.T.M.

J. T. THIJSSE, The new Hydraulic Engineering Laboratory at Delft, Holland, De Ing. (Bonev-en Waterbonwkunde), v. 49, pp. 175-184 [see Civ. Eng. Abs., v. 62, p. 151].

Illustrations and descriptions of large-scale models of harbors, etc. Some used for the purpose of studying wave-action.--Calif.

H. A. THOMAS, Hydraulics of flood movement in rivers, Pittsburgh, Carnegie Inst. Tech., 1934, 70 pp., diagrams, charts, tables [see also German abstract in V.D.I. Zs., v. 79, No. 18, p. 559, May 4, 1935].

The pamphlet presents elements of hydraulic theory of unsteady flow in open channels needed in solution of problems pertaining to movement of flood-waves in rivers and discusses various approximate methods used for handling them; useful to engineers interested in flood-control [Eng. Soc. Lib. N. Y.].--Calif.

H. THORADE, Probleme der Wasserwellen, Verlag Henri Grand, Hamburg, 219 pp., 1931.

This is a clearly written book relating mainly to ocean-waves but covering also flood-waves and effect of channel-friction on waves. The work of many investigators is reviewed and where this work has resulted in equations for wave-velocity, these equations are given and explained. The book is comparatively free from involved mathematical discussion.--R.E.H.

C. G. J. VREEDENBURGH, Een eenvondige afleiding van de formule van Airy voor de voortplantingssnelheid van golven in water met eindige diepte, Ingenieur, v. 49, No. 22, pp: 212-213, June 1, 1934.

Simple derivation of Airy equation for velocity of propagation of waves in water of finite depth; theoretical mathematical analysis.--Calif.

W. C. S. WIGLEY, Wave profiles and wave resistances, R. Soc. Proc., v. 144, pp. 144-158, March 1, 1934 [see Sci. Abs.-A, v. 37, p. 356, 1934].

An investigation is described for a form having a parabolic water-line, in its effect on the form of the waves it generates when moving on the surface of water.--Calif.

S. M. WOODWARD, Theory of the hydraulic jump and backwater curves, Miami Conser. Dis., Tech. Rep., Part 3, pp. 11-62, 1917.--R.E.H.

FLOOD-Flow Experiments of the Hydraulic Laboratory at Vicksburg, Mississippi, Eng. News-Record, v. 106, p. 970 [see Civ. Eng. Abs., v. 49, pp. 166-167, October, 1931].

Description of a test made to study the limits of backwater effect from a maximum all-time stage in the Mississippi with a flood-flow in the Illinois River, using an outdoor model.--Calif.

FLOODS in New England, Boston Soc. Civ. Eng. J., v. 17, pp. 285-464 [see Civ. Eng. Abs., v. 46, p. 173, 1931].

This paper is the Report of the Committee of The Boston Society of Civil Engineers appointed to investigate the discharge of the flood which occurred in New England in November, 1927. In addition to data on this particular flood, data and tables give information on floods for this region for the last two centuries and remedies are proposed.--Calif.

## Addendum

(Based on Letter from R. S. Goodridge dated April 13, 1939)

Henry FAVRE, Theoretical and experimental study of waves of translation in uncovered channels. Dunod, Paris, 1935, 215 pp.

Translation has been made by Soil Conservation Service and may be mimeographed for distribution upon request of workers in this field, subject to the restrictions required by the Office of Information.

Charles ELLET, Jr., Mississippi and Ohio rivers; containing plans for the protection of the delta from inundation and an investigation of the practicability and cost of improving the navigation of the Ohio and other rivers by reservoirs, published in Philadelphia, 1853.

This book contains many notes on the flow of the rivers above and notes the tendency of surface-craft to be pushed off the thalweg of the stream in flood while on a falling stage craft without assistance or guidance may be floated down stream in a trough. This indicates a strong convex-surface transverse-profile or crown on rising stages with possible velocity-components to the edges of the streams.--R.S.G.

General Peter Pierce Lyons O'CONNELL, The flood discharge of rivers, Inst. Civ. Eng., v. 27, pp. 207-217, 1868.

He observes that when a tributary in flood flows into a large main river, the channel of the latter acts very effectively as a moderator, the flood forming on the surface of the main river a wave, the summit of which is constantly being depressed as it travels down the river.--R.S.G.

Robert W. GAY,

Letter (1938) to me stating that A. S. Fry, Head Engineer, Hydraulic Data Division, TVA, will be able to release soon information on the movement of a flood-wave from the Norris Dam and the identification of the waters, through salts from the catchment in solution, much in arrears of the wave-front at some distance downstream. This is interpreted as indicating that flood-waves are propagated by a translation of pressure to some extent. Further information of an official nature is desired from the TVA as soon as possible. I believe that this is being prepared.--R.S.G.

John BRUNTON

Trans. Inst. Civ. Eng., v. 27, p. 227, quoting from report of Mr. McNeill, "The water came down in a succession of bores, the largest of which, bringing down with it the ruins of a village about a mile and a half up the river, came down with immense force, ... , carrying away 11 spans of girders, with their piers, as if they had been straws."--R.S.G.

J. ALLEN, Experiments on waves of translation in small channels, Bull. II, pp. 1-7, 1938, Internat. Ass. Hydraulic Structures Res., p. 44, The Whitworth Engineering Laboratories, The Victoria University of Manchester, under Prof. A. H. Gibson, Phil. Mag., Ser. 7, v. 25, p. 754, May, 1938.

Determination of velocities of propagation under various conditions of depth and height in a small flume and river model.--R.S.G.

Jarrett OLIVER

Hydrographer for the United States Geological Survey at San Bernardino, California, observed travel-waves in Strawberry Creek at Highland Avenue northeast of the city of San Bernardino, California, on March 2, 1938, during the height of Los Angeles Area Flood. At 1:00 p.m. he observed a continuous series of travel-waves, two to three feet high, moving at 15 to 20 feet per sec at about 10-sec intervals from a distance of one-quarter mile. The stream-bed slope is 1.5 to 2.0 per cent, width 50 feet. The waves had decidedly vertical tumbling fronts and diminished in depth to a flow of about 25 to 50 cfs during the later half of the interval between crests. Mr. Oliver stated that the waves at times carried concrete slabs and tossed them as though they were cork. The above account was given verbally by the observer to me upon inquiry for data on estimates of flood-flows made by him in his district.

W. G. Hoyt of the Washington Office of the United States Geological Survey says (April 12, 1939) that his Service is not prepared to report officially on the phenomena of travel-waves.--R.S.G.

Walter T. WILSON

Under date of February 16, 1939, I received a letter enclosing a report of rising-stage wave observed at West Tarkio Creek, Iowa, at the United States Geological Survey and Soil Conservation Service cooperative gaging-station on September 13, 1938, at 10:08 a.m. near Westboro, Missouri. Some pertinent descriptive notes from his statement follow: "Initial wave 0.8 of a foot high was followed by about five lesser waves about six to eight feet apart and travelling at 8.5 feet per sec. In one minute the wave-height was 1.27 feet; in 13, 2.42 feet; in 19, 2.58 feet, and in 25, 2.86 feet. Before the wave-passage the initial flow of about 40 cfs in a channel 43 feet wide was very smooth, and after the wave it was very rough. The flow at the crest of the wave is estimated to be about 1040 cfs. The stream carried considerable drift which followed the wave by about 500 feet. The waves were convex downstream about 15 feet in the width of 43 feet. The wave-crests appeared quite sharp with the troughs rounded. Seddon's relationship for wave-velocity, increment Q/A, 1000/118 = 8.48 feet per sec seems in good agreement with the observed velocity of the wave as measured by stop-watch over a reach determined to be 924 feet. The wave lost its identity in passing over the control-weir involving a fall of about three feet.

[Note: I am requesting a review of his data regarding $Q_s$ and areas with respect to the stages reported upon. Mr. Wilson had been put on the alert for such data on a contact of mine in Des Moines in 1937. I saw a similar wave in Colorado Springs, Colorado, after a severe rainstorm in 1936.]--R.S.G.

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Flattening of floods, pp. 16, 17, and plates (1, Lower Colorado River, 1938; 23, Lower Colorado River, 1938, Austin to Eagle Lake; 24, Lower Colorado River, 1936, Austin to Eagle Lake; 25, Lower Colorado River, 1935, Austin to Eagle Lake). Empirical method of reduction of flood peak-discharge by Trigg Twitchell (26, Lower Colorado River, San Saba to Austin, nine floods; 27, Lower Colorado River, Austin to Eagle Lake, ten floods; 28-32, conveyance of silt).--R.S.G.

UNITED STATES GEOLOGICAL SURVEY, Major Texas floods of 1936, Water-Supply Pap. No. 816.

Page 105, progressive reduction of crest of the Brazos River at Waco, near Bryan and at Richmond, Texas. Page 108, Lower Colorado River, near San Saba, Austin, Smithville, and near Eagle Lake, Texas.--R.S.G.

Bennett SWENSON, The Ohio and Mississippi River Floods of January-February 1937, Mon. Wea. Rev., Supp. No. 37, p. 47.

Graphs of the stages above flood-level taken by the floods of the Ohio and Mississippi rivers at 27 gages from Pittsburgh to New Orleans. These show the progressive reductions in stage effected by the channel-storage largely rather than the steepening of fronts or the overrunning of the preceding stages of flow by the flood-crests as is evidenced in the graphs of the Texas streams.--R.S.G.

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This late work develops criteria for the design of both rectangular and trapezoidal open flood-channels which are involved in super-critical flow, as below the spillways of dams. I have been using it in the review of a number of dams recently transferred to the Soil Conservation Service for operation and maintenance. The criteria permit an approximation of both the height and the position of the reflecting boundary-waves. There still is the question of the entrainment of air in prototype which must be estimated for freeboard-allowance.--R.S.G.

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## Appendix

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Robert E. HORTON, Channel waves subject chiefly to momentum control. (Contribution from Division of Research, Soil Conservation Service and Horton Hydrologic Laboratory, Voorheesville, New York, Washington, May 1938 [U.S. Dep. Agric., SCS-TP-16, mimeog., 51 pp.])

This paper describes a series of experiments made at the author's laboratory, using an experimental slope channel 5-5/8 inches wide and 120 feet in length, with recording gages at 25-foot intervals. Water was supplied from a constant-level orifice-box, with both screw and level movements, so that the rate of flow could be changed either abruptly or gradually. Altogether about 190 experiments were carried out, the results of which are given in the paper. Cases covered include, for different slopes and depths, the following: Instantaneous increase in discharge; instantaneous decrease in discharge; gradual increase in discharge; gradual decrease in discharge; waves with triangular profile; waves with rectangular profile; disturbance waves in still water; and alternating waves, such as occur when an outlet is opened or closed in a pond. No attempt is made to develop a new formula for wave-velocity, but in conjunction with the observed velocities and other data there is given for each experiment the velocity of the wave for the same conditions as computed by two formulas of Bazin-Darcy, by the Leach-King formula, and the Koch and Carstanjen formula, and it is shown that all of these formulas give reasonably good agreement with the experimental data for simple increment waves. The phenomena of alternating waves which travel successively upstream and downstream through a mill-pond are particularly interesting, as it is shown that the water-level in the pond changes abruptly by definite quanta each time the wave changes direction at one end of the channel.

In conclusion, the author points out that in these experiments the effect of channel-friction was apparently relatively small, and waves of the character of those covered by the experiments are subject chiefly to momentum-control. In the case of triangular and rectangular waves, the wave-length did not exceed 1000 to 2000 times the wave-height. The author points out that in the case of natural river-floods, the wave-length is oftentimes of the order of 25,000 to 100,000 times the wave-height, and suggests that there is a gradual transition for waves of the same type as between short waves (that is, wave-length less than 1000 times wave-height) and long waves, such as occur in river-channels, with an increasing degree of channel-friction control and a decreasing effect of momentum as the ratio of wave-length to wave-height increases.--R.E.H.

Robert E. HORTON, Definitions and classification of flood waves, Bull. Perm. Internat. Ass. Navigation Congr., No. 25, January 1938.
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State University of Iowa, Iowa City, Iowa, April 1939
The Pennsylvania State College, State College, Pennsylvania (after July 1, 1939)

# APPENDIX B--REPORT OF SUB-COMMITTEE ON CURRENT-INVESTIGATIONS OF SPECIAL COMMITTEE ON FLOOD-WAVES

H. A. Thomas, Chairman

During the year which has elapsed since the presentation of the April, 1938, Report of the Sub-Committee on Current-Investigations on Flood-Waves, the following additional items have been noted with regard to investigations in progress in the United States. It is not implied that this list is exhaustive. No additional data on foreign investigations have been received.

(1) The Division of Research, Soil-Conservation Service, United States Department of Agriculture, in cooperation with the Horton Hydraulic Laboratory, Voorheesville, New York, has brought out a publication written by Robert E. Horton and entitled "Channel-waves subject chiefly to momentum control." The fact that experiments on such waves were in progress in the Horton Hydraulic Laboratory was mentioned in the Report of our Sub-Committee for last year. The experiments described in the publication were performed in a wooden channel 130 feet long by 6-5/8 inches wide, with typical flow-depths of from one to six inches. The types of waves studied included the instantaneous increase, instantaneous decrease, gradual increase, gradual decrease, triangular, rectangular, and alternating. The velocities of these waves were compared with values computed by several well-known equations applicable to waves in which the effects of friction are negligible, the Koch-Carstanjen equation generally giving the best results. The publication calls attention to the desirability of making additional experiments in a much longer channel in order to study waves more comparable to typical flood-waves in rivers, where the effects of friction are more important than those of momentum.

(2) A bulletin has been published by the University of Iowa (Studies in Engineering, Bull. No. 14), entitled "A study in flood-waves," and written by Elmer E. Moots, Professor of Mathematics and Civil Engineering, Cornell College, Mount Vernon, Iowa. This bulletin contains a discussion of the mathematical theory of several types of flood-waves and waves of translation, and also a description and results of experiments on waves of translation conducted in a wooden rectangular channel 52 feet long by 8-1/16 inches wide, typical depths of flow from one to six inches being employed.

The waves studied were of the type described as "sudden increase" by Mr. Horton in the preceding item. The fact that these two sets of experiments on the same phenomenon and in closely similar apparatus have been recently conducted and the results published by two different American laboratories, emphasizes the justification and necessity for the efforts being made by the Hydrologic Division of the American Geophysical Union to coordinate the activities of research-workers in the hydraulic laboratories of this country and of the world.

(3) A paper on "Flood-routing" by E. J. Rutter, Q. B. Graves, and F. F. Snyder was published [Proc. Amer. Soc. Civ. Eng., February, 1938] but was not received in time for mention in last year's Report of this Sub-Committee. This paper describes the procedure developed by the engineers of the Tennessee Valley Authority for routing floods through the Tennessee River in order to predetermine the effects of various dams in modifying flood-stages. While in their broad aspects, the flood-routing methods described in this paper are not essentially different from ones which have been used in other previous investigations, nevertheless a description of the application and extension of these methods to meet the special problems encountered on the complex river-system of the Tennessee constitutes an important contribution to the literature on flood-waves and reflects current progress in the development of practical methods to analyze flood-wave phenomena on actual river-systems.

(4) A monograph entitled "The unit-hydrograph and flood-routing" was prepared by Gerald T. McCarthy for presentation at the Conference of the North Atlantic Division of the United States Corps of Engineers at New London, Connecticut, June 24, 1938, this being published in limited edition in the United States Engineer Office at Providence, Rhode Island. This describes the "coefficient"-method of flood-routing, which is reported to have been used with marked success in recent flood-routing studies, especially those on the Muskingum River System in Ohio and the Connecticut River System in New England. This method is considered to be an improvement over previously used methods, chiefly in making a definite allowance for "wedge-storage" effects and in more systematic utilization of the available natural flood-flow data. Its original features are said to be especially due to the work of Mr. McCarthy.

(5) A publication has been prepared by the United States Engineer School at Fort Beloir, Virginia, explaining the most approved methods of flood-routing and describing recent developments in this field. This publication is entitled "Engineering construction and flood-control" [v. V, Flood Routing, Pub. No. X-152].

(6) Recently a number of models intended to solve problems of unsteady-flow rivers and other open channels have been constructed in various hydraulic laboratories in the United States. In the present state of the art of flood-control engineering, many engineers feel that the use of such models represents the most advanced and practical method now available for solving the differential equations of flood-movement in conformity with the complex boundary-conditions defined by the channels of a river-system. The general requirements for such models demand an exaggeration of the vertical scale in comparison with the longitudinal scale, in order to insure turbulence of flow.

The largest of these models is that constructed in the United States Waterways Experiment Station at Vicksburg, Mississippi, to represent the entire lower Mississippi Drainage-Basin, the approximate maximum length and width of the model being 1500 feet and 200 feet, respectively. Inflow rates on the various tributaries are simulated by manually controlled valves. While this model has been in existence for several years, it is being so constantly modified and improved that the recent studies conducted by its aid to study the effects of cut-offs on the Mississippi River are quite properly listed in this report on "current-investigations."

A distorted-scale model representing the Allegheny-Monongahela River System, together with a portion of the upper Ohio River System, has been constructed at the Carnegie Institute of Technology to study problems of flood-control on these rivers, and during the current year a report on the results obtained with this model to date has been submitted to the United States War Department. Because of the great exaggeration of the vertical scale (vertical 1:80, horizontal 1:18,000), the term "hydraulic integrating machine" describes this apparatus more correctly than the term "model." Inflow hydrographs on the tributaries are simulated by cam-controlled needle-valves. Detailed investigations comparing the accuracy, reliability, and cost of the model results with those obtained by paper computations are now in progress.

Several models representing flow in tidal channels have been constructed in this country recently. Since these models are essentially integrating machines for solving the partial differential equations of unsteady flow in open channels, the gradual improvement taking place in the technique of their construction and operation has an important bearing on the development of related methods for solving flood-wave problems. Among models of this type may be mentioned the Cape Cod Canal Model at Massachusetts Institute of Technology and the models of Galveston Bay (Texas), East River (New York), Hilo Harbor (Hawaii), and Chesapeake and Delaware Canal (Delaware), of the United States Waterways Experiment Station at Vicksburg. An outstanding development in these models is the use of electrical methods for controlling and recording the instantaneous water-elevations.

(7) During the past four years a research on travelling waves in steep channels has been in progress at the Carnegie Institute of Technology under the auspices of the American Society of Civil Engineers' Special Committee on Hydraulic Research. During the present year this investigation is being directed toward a study of the effect of a bed-deposit of sand, gravel, or boulders in modifying the profile of travelling flood-waves. This aspect of the investigation was especially suggested by the behavior of flood-waves in the steep river-channels of the Los Angeles District during the disastrous floods of 1938. Flood-stages were reported to have been materially increased by the presence of moving barriers of boulders and rock-debris in the stream-channels, the phenomenon of concentration of such materials in movable masses being associated with flow at velocities near the critical. A wooden channel 42 feet long is being used in this study.

(8) The Annual Bulletin on "Current hydraulic laboratory research in the United States," published by the National Bureau of Standards, has just been issued in April, subsequent to the preparation of the foregoing report, and lists the following additional projects:

(423) Flood waves in open channels: University of California--This refers to the completion of the work described in last year's Sub-Committee Report and conducted in a small channel of variable slope with a gate at its upper end so arranged that the discharge could be varied through any predetermined cycle. Place of publication not mentioned; correspondent, Professor Raymond Boucher.

(889) Characteristics of bore-waves: Stanford University--To study the characteristics of the transmission of bore-waves around bends and into constricted or expanded sections, and means of reducing or eliminating a bore after it has once started. In construction-stages. Correspondent, Professor J. Hedling.

(898) Travel of surge-waves in open channels: University of Wisconsin--To determine the rate of travel of surge-waves and the effect of variations in the depth and width of channel on this rate of travel. A rectangular wooden flume, one foot wide by 80 feet long, is being used, means of widening the flume in certain places being provided. Experimental work is in progress. Correspondent, Professor J. G. Woodburn.

(977) Flood-waves mathematical theory--A cooperative research conducted by the National Bureau of Standards and the United States Weather Bureau, the results to be coordinated and presented in a series of papers. Correspondent, the Director, National Bureau of Standards.

Carnegie Institute of Technology,
Pittsburgh, Pennsylvania

## REPORT OF THE COMMITTEE ON CHEMISTRY OF NATURAL WATERS, 1938-39

C. S. Howard, Chairman

The membership of this Committee is as follows:

C. S. Howard (Chairman), United States Geological Survey, Washington, D. C.
I. A. Denison, National Bureau of Standards, Washington, D. C.
W. P. Kelley, 119 Hilgard Hall, University of California, Berkeley, California
A. C. Lane, 22 Arlington Street, Cambridge, Massachusetts
C. S. Scofield, Bureau of Plant Industry, United States Department of Agriculture, Washington, D. C.
D. G. Thompson, United States Geological Survey, Washington, D. C.
T. G. Thompson, University of Washington, Seattle, Washington

Studies on the corrosion of metals and soils have been continued at the National Bureau of Standards and a report of the recent findings was published under the title "Correlation of the electrolytic corrosion test with the active corrosiveness of soils," by I. A. Denison and R. B. Darnielle [J. Res., Nation. Bur. Stan., No. 21, pp. 819-830, December, 1938]. Another paper on this subject by Kirk H. Logan was published under the title "Engineering significance of National Bureau of Standards soil corrosion data" [J. Res., Nation. Bur. Stan., pp. 109-125, January, 1939].

During the post-war period extensive investigations of the corrosion of metals in natural waters, under conditions of total and partial immersion, have been conducted by two groups of investigators under the direction, respectively, of Dr. U. R. Evans of the Metallurgical Laboratories of Cambridge University and Dr. G. D. Bengough of the Chemical Research Laboratory, Teddington, England. As several of the major conclusions reached by these two groups were contradictory or at least very difficult to reconcile, conferences have been recently held for the purpose of resolving the main points at issue. As a result of these conferences an article was published under the title "The corrosion of metals by salt solutions and natural waters: An agreed statement," by G. D. Bengough, U. R. Evans, T. P. Hoar, and F. Wormwell [Chemistry and Industry, v. 57, pp. 1043-1047, November, 1938]. Excerpts from this paper follow (G. D. Bengough and F. Wormell are of the Chemical Research Laboratory at Teddington, and U. R. Evans and T. P. Hoar are of the Metallurgical Laboratories of the Cambridge University).

### Excerpts from "The corrosion of metals by salt solutions and natural waters: An agreed statement"

Electrochemical mechanism--It is generally agreed that most wet-corrosion processes are connected with electric currents passing between anodic and cathodic places, that primary corrosion usually occurs at the anodic areas, and that the development or non-development of attack is largely decided by the solubility of the anodic and cathodic products. Three cases can be distinguished:

Case (1): The anodic and cathodic products are both freely soluble--Corrosion usually proceeds rapidly at certain parts of the metallic surface. Thus, iron is corroded by sodium-chloride solution, since the anodic and cathodic products (ferrous chloride and sodium hydroxide) are both soluble, although they subsequently interact to precipitate mixed oxides (rust), often out of physical contact with the metal, as loose non-protective deposits over portions of the surface and elsewhere.

Case (2): The cathodic product is sparingly soluble--In this case, the cathodic product, if deposited in close contact with the metallic surface, may sometimes "poison" the cathodic reaction and retard the corrosion-process. Corrosion is frequently slower in solutions of calcium, magnesium, and zinc salts than in solutions of the corresponding sodium salts. Hard waters which contain calcium bicarbonate tend to throw down calcium carbonate in the cathodic regions (where the pH rises locally) and this may interfere with the cathodic reaction and reduce the corrosion-rate; later, the calcium-carbonate deposit often interacts in situ with anodically formed iron salts to give a compact rust, and this may also tend to slow down corrosion. Calcium bicarbonate in water does not slow down the corrosion if there is present "aggressive" carbonic acid, that is, carbonic acid in an amount greater than that needed to hold the calcium carbonate in solution. A water cannot be expected to be non-corrosive if it is capable of dissolving calcium carbonate when left in contact with the latter. Unfortunately, the converse is not true; certain waters (especially saline waters) may be in equilibrium with calcium carbonate and may yet be capable of rapid attack on iron.

Case (3): The anodic product is sparingly soluble--While salts which yield sparingly soluble cathodic products frequently diminish the corrosion, those which would yield sparingly soluble anodic products often almost prevent it, stifling the anodic attack at susceptible points before ever it becomes visible. Iron will remain bright indefinitely in dilute alkali or in sodium-phosphate solution. The use of these bodies as inhibitors in corrosive waters is well known, but it is not always without danger. Thus, if a sodium-chloride solution is treated with sodium hydroxide, carbonate, or phosphate in amounts just insufficient to prevent corrosion altogether, the total amount of corrosion may be diminished, but the corroded area is diminished still more, so that the intensity of corrosion (corrosion per unit area of the part affected) is actually increased, and perforation may be produced more quickly than if there had been no attempt to treat the water.

The function of oxygen--The main function of oxygen is that of a depolarizer of the cathodic reaction; metals which cannot expel free hydrogen from the liquid surrounding them will suffer corrosion only if oxygen or other depolarizer is present. [The word "depolarizer" is used here as being familiar to readers, but it should not be taken to imply that hydrogen is first deposited and then removed by oxygen. Probably the oxygen is first adsorbed, and its presence stimulates the discharge of hydrogen ions at points where (except in comparatively acid solutions) they would not otherwise be discharged (or at least not discharged readily). The interaction of $H^{\cdot}$ with adsorbed O will give one $(OH)'$ ion, and since another $(OH)'$ is left unbalanced, each adsorbed O atom gives two $(OH)'$ ions. Instead of picturing the interaction of a hydrogen ion with oxygen, a water-dipole (which is a polar molecule that can be represented HO - H) may interact with oxygen. In either case the production of alkali at places reached by oxygen can be written $HO - H + O + 2e = 2(OH)'$.] Moreover, in cases (1) and (2) considered above, the rate of corrosion usually increases with the rate of supply of oxygen to the metal. An example of case (1) is iron or steel in N/10 or N/2 sodium or potassium chloride. Here the rate of corrosion has been shown to increase with the rate of oxygen-supply by conducting experiments under standardized conditions, with turned specimens totally immersed in stagnant solutions.

Oxygen also serves to convert ferrous compounds to ferric, and the color and compactness of the ultimate corrosion-product largely depends on the oxygen-supply; a strip of iron which gives a reddish-yellow ferric rust if corroded in a broad beaker may give a black or greenish magnetite rust if corroded in a narrow tube. Finally, in the case of those alloys which form highly protective oxide films, oxygen may serve to maintain these films and thus prevent corrosion. This explains why an alteration of oxygen-pressure in the atmosphere may produce different effects in different cases. In the case of iron corroding in various salt solutions, anything which increases the supply of oxygen will--in general--increase the rate of attack; in fact, the oxygen-supply is a very important controlling factor. Certain chromium alloys, however, corrode less quickly in the presence of much oxygen than under relatively anaerobic conditions, where the protective oxide-films, on which resistance depends, cannot be adequately maintained. Even on iron oxygen may act as an inhibitor under certain special conditions; if iron is placed in a chloride solution and oxygen is forced into the space above the liquid under pressure, rapid corrosion occurs, the rate of attack increasing with increase of pressure up to 25 atmospheres. But if the oxygen is introduced under pressure before the introduction of the liquid, then it is found that high pressures produce less corrosion than low pressures.

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Analytical work on samples collected in connection with density-current studies in Lake Mead has been continued during the past year. Results obtained in these studies were used in the preparation of two papers presented by W. D. Collins and C. S. Howard before the Division of Water, Sewage, and Sanitation of the American Chemical Society. Stratification of water of different densities and chemical composition has been found in several parts of the lake.

During the year, the analytical data obtained in connection with the Rio Grande Joint Investigation, mentioned in the Committee's Report for 1936-37, have been published as "Quality of water of the Rio Grande Basin above Fort Quitman, Texas," by Carl S. Scofield [U. S. Geol. Sur. Water-Supply Pap. 839]. This report presents the analytical data used as a basis for the quality-of-water section of the report prepared by the National Resources Committee entitled "Regional planning: Part 6, Upper Rio Grande." In the report of the National Resources Committee one section of the quality-of-water part of the report is devoted to a discussion of the significance of the sodium constituent of irrigation-water. Two paragraphs from this section of the report are quoted below:

"It has been abundantly shown that the effect of sodium in solutions in contact with the soil is deleterious to the physical properties of the soil. This is brought about through reactions of base-exchange by which sodium from the solution tends to replace calcium that is combined with the soil, the calcium in turn passing into solution. Such exchange reactions are well known and are extensively utilized in the zeolitic process of water softening.

"The deleterious effects of sodium combined with the soil are manifested by dispersion of the soil-particles, and by impairing the permeability of the soil to the absorption of water or the movement of water through it. Soils containing much combined sodium are also more difficult to work into good tilth than the same soils containing less combined sodium."

Samples have been collected continuously since October, 1934, under a project of the Works Progress Administration, sponsored by the State Water Commission of Connecticut and supervised by the United States Geological Survey, to obtain basic facts concerning the salinity of the Connecticut River and the variations in the chloride-content of ground-water in the coastal areas of Connecticut. One mimeographed report gives the results of the studies of the salinity of the Connecticut River during a three-year period, and six other reports, giving the results of water-level observations, have also the results of a large number of chloride-determinations on samples of ground-water. These reports were distributed by the Works Progress Administration and have been made available to many libraries in Connecticut and adjoining States. The results obtained during the salinity-studies show the extent of sea-water intrusion under different conditions of river-stage and velocity and direction of wind.

U. S. Geological Survey,
Washington, D. C.

## REPORT OF THE COMMITTEE ON RAINFALL, 1938-39

Merrill Bernard, Chairman

The activities of the Committee on Rainfall for the past year are reported upon under the following headings:

International bibliography--Contributions to American literature in the field of rainfall-measurement and analysis were assembled and abstracted for the international bibliography by Miss Mary O. Soroka, member of the Committee. Miss Soroka had prepared the Committee's contribution to the bibliography for the year 1937 and the Committee is again indebted to her for this distinctly important service.

Hydrometeorological studies--The hydrometeorological studies of storm-rainfall made by the United States Weather Bureau for the United States Corps of Engineers are progressing satisfactorily. There are now 26 persons engaged in the studies. Authorization has been given to expand the project to include special studies for the conservancy-agencies of the Department of Agriculture. The objective of these investigations is to delineate, for particular basins involving the design of flood-control works, the maximum possible storm. Methods and techniques are rapidly being improved. To date the Hydrometeorological Section of the United States Weather Bureau has issued reports on seven specific basins and has analyzed in varying degree approximately 200 storms.

Storm morphology and micro-climatic studies--The Section of Climatic and Physiographic Research of the Soil-Conservation Service has continued its investigational work in the morphology of storms and in gathering micro-climatic data. It has:

(1) "Kept in continuous operation over 500 recording rain-gages in the 8000 square miles of the Muskingum Watershed in Ohio. In order to make these micro-climatic data generally available and at the same time to present them in a readily usable form, maps of precipitation by half-hour and total storm-periods have been drawn up and are to be reproduced.

(2) "Assembled rainfall-data during the year from approximately 150 recording gages in the upper Ohio and Susquehanna drainage-basins, covering all of the State of Pennsylvania and adjacent portions of New York, West Virginia, and Ohio. These gages are maintained by the Pennsylvania Power and Water Resources Board, the Pennsylvania Power and Light Company, the Pennsylvania Electric Company, the City of Meadville, Pennsylvania, the New York Metropolitan Water-Supply Company, the United States Engineers, the United States Forest Service, the United States Geological Survey, the United States Weather Bureau, and the United States Soil-Conservation Service. These data, together with those from the Soil-Conservation Service gages in the adjacent Muskingum Basin, have made it possible to prepare and reproduce detailed hourly precipitation maps of the area comprised in the Muskingum, upper Ohio, and Susquehanna drainage-systems.

(3) "Since September 1938 has been carrying out an investigation to determine the drought-frequency for all parts of the United States. This will result in the formulation of quantitative

expressions of seasonal and annual drought-hazard for all sections of the country."

Rainfall studies by the United States Geological Survey--The rainfall-observations at about 1000 locations for the Ohio River Flood of December, 1936, to January, 1937, were analyzed, and isohyetal maps were prepared. Differences between rainfall and runoff and infiltration-capacities were determined for all major and minor basins in the Ohio River drainage above Cairo.

Similar studies were made of the storm of December, 1937, in central and northern California. The records of about 1600 precipitation-stations were analyzed in these studies.

An analysis was made of the intensive storm of August 6-7, 1935, in the Muskingum River basin; 108 records of precipitation including 37 unofficial records of storm-rainfall have been compiled and used as the basis for the preparation of an isohyetal map.

In connection with the floods in New England during September, 1938, analyses are now being made of about 700 precipitation-records including about 100 continuous records.

Nation-wide network of rainfall-intensity stations--A rapidly growing appreciation for the need of a greater number of rainfall-stations equipped with intensity rain-gages has initiated a cooperation between the United States Corps of Engineers and the United States Department of Agriculture under which the United States Weather Bureau will inaugurate a Nation-wide network of such stations. The contemplated service will bring into the network all existing precipitation-stations and will establish additional ones where needed. The initial density of the proposed network will be approximately one station to 400 square miles.

Other activities--The Chairman of the Committee has served on Sub-Committees of the Water Resources Committee in (1) preparation of standardized forms for the tabulation of hourly rainfall and excessive rainfall, and (2) preparation of a manual on the design of low dams.

The Chairman regrets to report the resignation of Mr. Charles W. Sherman from the Committee. The membership of the Committee is now as follows:

W. W. Horner, Consulting Engineer, International Office Building, St. Louis, Missouri
W. G. Hoyt, Geological Survey, United States Department of Interior, Washington, D. C.
Dr. J. B. Kincer, Weather Bureau, United States Department of Agriculture, Washington, D. C.
Carroll F. Merriam, Pennsylvania Power Company, Lexington Building, Baltimore, Maryland
Professor Thorndike Saville, Dean, College of Engineering, New York University, University Heights, New York
L. K. Sherman, Consulting Engineer, 53 West Jackson Boulevard, Chicago, Illinois
Miss Mary O. Soroka, c/o Division Engineer Office, United States Engineers, New York, New York
Dr. C. W. Thornthwaite, Head, Section of Climatic and Physiographic Research, Soil-Conservation Service, United States Department of Agriculture, Washington, D. C.
H. C. Willett, Meteorological Division, Massachusetts Institute of Technology, Cambridge, Massachusetts
Robert E. Horton, Consulting Engineer, Voorheesville, New York
David E. Donley, Tennessee Valley Authority, Knoxville, Tennessee
Merrill Bernard (Chairman), Washington, D. C.

U. S. Weather Bureau,
Washington, D. C.

## REPORT OF HYDROLOGIC ADVISORY COMMITTEE TO THE RESEARCH DIVISION OF THE UNITED STATES SOIL CONSERVATION SERVICE

Robert E. Horton, Chairman

Membership of the Committee is as follows: J. E. Church; W. W. Horner; A. F. Meyer; C. M. Saville; L. K. Sherman; Samuel Shulits; R. N. Towl; F. J. Veihmeyer; Robert E. Horton (Chairman). The Executive Sub-Committee consists of Messrs. Horner, Sherman, and the Chairman. A Special Sub-Committee to deal with all phases of surface- and channel-erosion, transportation, and sedimentation was appointed in 1938, consisting of R. N. Towl and Professor Samuel Shulits (Chairman).

Meetings of the Advisory Committee have been held at Washington on an average of at least once a month during the past year. As a rule these meetings are attended only by members of the Executive Sub-Committee. Thus far these members only have been provided with transportation.

Other members of the Committee are kept in touch with the work by correspondence. In addition to these meetings various members of the Committee have inspected Soil Conservation Service field-experiment research work accessible to them and have assisted and advised field-men directly and by correspondence in carrying on their work. The Chairman has inspected the Watershed and Hydrologic Studies at Freehold, and the Soil and Water Conservation Experiment Stations at Marlboro and Beemerville, New Jersey, Marcellus, New York, and the Hydraulic Laboratory at Spartanburg, South Carolina. W. W. Horner has undertaken to follow closely the experimental work at Edwardsville, Illinois. In addition to other meetings, a meeting was held at Coshocton, Ohio, Experimental Watershed, May 2-3, 1938, attended by Messrs. Horner, Sherman, and the Chairman and by about one hundred other persons, including Dr. W. C. Lowdermilk, Chief of the Research Division, and also C. E. Ramser, of the Soil Conservation Service, who acted as Chairman. In addition there were present representatives of other United States Government bureaus interested in hydrologic research, including the United States Forest Service, United States Weather Bureau, and United States Geological Survey. In addition to a field-inspection, a full day was spent in the discussion of problems and methodology of hydrologic research.

It is the purpose of the Committee to:

(1) Aid in securing the best possible research results in scientific hydrology from the field-research work of the Soil Conservation Service.

(2) Aid in laying a sound scientific hydrologic basis for use of the field-research results and data in connection with problems including: (a) Flood-control on the ground-surface, by increasing infiltration-capacity and reducing surface-runoff; (b) better water-economy in land-use through the same means; (c) reduction of soil-surface erosion.

Some of the problems submitted to and studied by members of the Committee, and discussed at its meetings, include:

(1) Publication of field-experimental data, including preparation of form for such publication-- Members of the Committee favor publication of original data in sufficiently complete form so that any one may use it for any purpose for which it will serve. This result may best be accomplished by publishing a small edition of research data without attempting complete analysis in the first instance. The Committee understands that results in this form, covering runoff-data from small drainage-basins, will soon begin to appear.

(2) Methods of analysis of data obtained from small drainage-basins and sprinkled-plat experiments--This includes determination of infiltration-capacity and its variation, determination of the law of surface-runoff, and the study of erosion-phenomena and their relation to quantity, depth, and velocity of overland-flow. In this connection, the Chairman prepared a paper on the "Analysis of simulated rainfall-experiments," published by the Soil Conservation Service in June, 1938. This covers only cases where the infiltration-capacity "f" remains sensibly constant during the experiment. A second paper, on the "Interpretation and application of runoff-plat experiments with reference to soil-erosion problems" was also prepared by the Chairman and will be published in the Proceedings of the Soil-Science Society of America for 1938. A third paper, on the "Analysis of runoff-plat experiments with varying infiltration-capacity" has been prepared by the Chairman and was presented at the twentieth annual meeting of the American Geophysical Union [see these Transactions, pp. 693-711].

(3) Design of apparatus for applying water to sprinkled plat--Artificial sprinkled plats afford many advantages as compared with plats subject only to natural rainfall. The Committee has strongly recommended the extension of this phase of the work. Among other advantages is the fact that with a relatively dry climate, as much data may be obtained in a month with a sprinkled plat as could be obtained in a year or more from natural rainfall. Furthermore, the rain-intensity can be kept constant and the constant intensity can be changed at will. The results are therefore more completely under control and more readily analyzed. Much attention has been given to the design of simple, portable, practicable apparatus for the application of water to sprinkled plats.

(4) Outline of analysis of hourly rainfall and runoff-records and the determination of areal average infiltration-capacities, using existing records of rainfall and runoff--This is an important subject because a large part of the work of the Soil Conservation Service must ultimately be based on existing data, modified and applied in accordance with the results obtained from the experimental plats and areas.

(5) A vast amount of hydrologic experimental data collected by the Soil Conservation Service remains unanalyzed and unused. This is particularly true of the results obtained on strip-plats. These are plats subject to natural rainfall but with varying vegetal cover and methods of soil-treatment. In general, hitherto, only the total runoff has been determined. The Committee has strongly recommended: (a) Compilation and early publication of the results obtained from such plats; (b) installation of recording runoff-gages, so that a complete hydrograph can be obtained and a complete analysis made of the runoff-phenomena from each plat (the Committee understands

that installation of recording runoff-gages on individual plats is now being undertaken).

(6) While the Advisory Committee was appointed initially to cooperate with the Research Division of the Soil Conservation Service, during the past year it was called in consultation concerning flood-control problems of the Department of Agriculture. Several meetings were held with Dr. Austin L. Patrick, Chief of the Division of Watershed and Conservation Surveys in the Soil Conservation Service, and others interested, and with the Flood-Control Coordinating Committee of the Department of Agriculture, of which Arthur C. Ringland is Chairman. Messrs. Horner and Horton were asked to prepare and did prepare extended outlines suggesting methods of collecting and utilizing hydrologic data in connection with problems of flood-control on the ground-surface.

It is not the purpose of this Report to describe results obtained from the Soil Conservation Service experimental work. Mr. Goodridge has given details regarding the observations of rainfall, runoff, and sedimentation of the United States Soil Conservation Service elsewhere in these Transactions [see pp. 525-539]. It may be, however, that out of the experimental work some comparatively new things are emerging:

(1) The occurrence of subdivided flow, or surface-runoff retarded by grass-cover in such a way that the velocity varies nearly in direct proportion to the depth of overland flow.

(2) The occurrence of rain wave-trains on experimental plats. Many examples of this somewhat obscure phenomenon have been observed.

(3) The occurrence of bore-flow or, more properly, minute mud-flows, in which the resistance of the viscous mud-front at the beginning of runoff predominates; its depth increases with the depth of water behind it. The velocity is very low compared with free hydraulic flow at the same depth and--strangest of all--the rate of runoff is nearly independent of the depth of flow, and the velocity varies more or less inversely as the depth. Taken altogether, these and other results constitute the beginnings of a new branch of hydrologic hydraulics, which might be described as micro-hydraulics. It involves phenomena which apparently occur naturally only in connection with surface-runoff or overland-flow, and which are as different from ordinary experience as were the experiences of Alice in Wonderland.

The members of the Committee have collectively devoted the equivalent of more than a year's solid time of one man to its work during the past 12 months. Their compensation has been in the opportunity to observe and study the very fundamentals of hydrologic phenomena, an opportunity for which some of them have waited nearly a lifetime.

The Committee makes grateful acknowledgment to Dr. W. C. Lowdermilk, Chief, and to Dr. M. L. Nichols, Acting Chief, Research Division, Soil Conservation Service.

Voorheesville, New York

## REPORT OF JOINT COMMITTEE ON HYDROLOGIC RELATIONS BETWEEN THE SECTION OF HYDROLOGY OF THE AMERICAN GEOPHYSICAL UNION AND THE DIVISION OF SOIL AND WATER CONSERVATION OF THE AMERICAN SOCIETY OF AGRICULTURAL ENGINEERS

H. S. Riesbol, Chairman

The basic objective of this Committee (established in February, 1939) as conceived by its sponsors is to coordinate the program and activities of those divisions and the committees of the two societies which are engaged in the field of agricultural hydrology.

The Committee at the present time consists of Messrs. J. G. Sutton, J. C. Marr, and H. S. Riesbol, representing the American Society of Agricultural Engineers, and Messrs. B. S. Barnes, D. B. Krimgold, and C. E. Ramser, representing the American Geophysical Union. The Committee has elected H. S. Riesbol as Chairman.

Correspondence between the Chairman and the members of the Committee has brought forth various suggestions regarding the formation and activity of the Committee, which suggestions are herewith presented:

L. K. Sherman--I would be heartily in favor of such an arrangement. It might avoid duplication of effort and be of mutual assistance in a program of common interests.

As a procedure for carrying out this cooperative relationship, I suggest the following and will be pleased to have you bring it to the attention of the American Society of Agricultural

Engineers or their Committee on Hydrology: The Section of Hydrology of the American Geophysical Union to appoint a Committee on Hydrologic Relations; the American Society of Agricultural Engineers to also appoint such a Committee which might be a committee of six (three members from each organization) and this Joint Committee to elect its own Chairman who would be a member of both organizations.

For the Section of Hydrology of the American Geophysical Union, the Committee to report to the Chairman of the American Geophysical Union Advisory Group to the Soil Conservation Service, Dr. Robert E. Horton, Chairman.

As to the American Society of Agricultural Engineers, I take it that this Joint Committee would probably report to its Committee on Hydrology.

C. E. Ramser--In discussing the work of this Committee with Mr. Sherman I inferred from his remarks that its primary purpose would be to delineate hydrologic activities of the two organizations. He feels quite strongly that the work of the American Geophysical Union should be devoted largely to pure science, that is, more to the theoretical and basic aspects of hydrology and that the work of the American Society of Agricultural Engineers should be devoted to the practical and engineering aspects from the standpoint of its application to specific problems.

R. E. Horton--One function of the Coordinating Committee would be to bring to the attention of standing committees of the Section of Hydrology a description of work on the lines in which they are particularly interested, which is being carried out by the Agricultural Engineers Committee, and vice versa.

There is another matter which I think might be worked out and would be eminently desirable, if practicable, and that is to arrange for an exchange of publications on hydrology between such members of the Section of Hydrology who are not members of the American Society of Agricultural Engineers as express a desire to secure the hydrologic publications of the latter, and vice versa. In the case of members of the American Society of Agricultural Engineers who are not members of the Section of Hydrology, but desire to secure papers on hydrology published by the latter, this could probably be worked out by making additional reprints, provided a list of those entitled to receive them was available to the General Secretary.

Bertram S. Barnes--It has been my opinion for a long time that one of the things most urgently needed in our field is the dissemination of information in regard to experimental data which has been and is now being obtained by various agencies so that the basic data could be obtained and utilized by students of hydrologic problems. I do not know whether our Committee could properly exert any pressure in this direction or not.

John G. Sutton--On February 16 you wrote me sending a copy of the proposed questionnaire to various directors of State colleges, and Government agencies engaged in agricultural hydrology. I think that the coordination of this with the American Geophysical Union should represent our first approach to the problem. Obviously, so much of the work being done on agricultural hydrology is being done by the United States Soil Conservation Service that the cooperation of the Director and his staff will have to be secured if effective work is to be done by the Committee.

With this in mind I have written to Mr. Jones and asked him to secure the suggestions of Dr. Nichols and Mr. Ramser concerning the need for a survey along the lines proposed in your letter of February 16. If the reaction is favorable I think that we should make this survey a joint endeavor with the American Geophysical Union and have it as one of the principal lines of work of the Joint Committee.

Similarly the proposal by Mr. Hickok to secure the needs for the members could very well be made a joint endeavor, in fact it might be advisable to give all members of the Committee an opportunity to study the data available on agricultural hydrology. These projects are quite large from a view-point of Committee undertaking and if we are to succeed we must secure a maximum of cooperation and create interest in the project.

James C. Marr--The Committee on Irrigation of the Soil and Water Conservation Division, American Society of Agricultural Engineers, is at present engaged in the preparation of a glossary of terms pertaining to irrigation. This undertaking is nearing completion and it is thought that it will soon be out of the way. I know that J. C. Christiansen, Chairman, and members of this Committee have not yet outlined a program of new work. I am, therefore, in the dark as to what line of endeavor the Section of Hydrology of the American Geophysical Union might undertake which assuredly would not duplicate future activities of the Soil and Water Conservation Division of the American Society of Agricultural Engineers. The only thought that I have in the matter is that we might do something to forward water-supply forecasting based on snow-surveys. The American Geophysical Union has displayed a great deal of interest in this somewhat new activity, and I have much to do with it in western United States. It is my understanding that the United States Weather Bureau is undertaking similar work in the eastern part of the United States. It is thought, therefore, that the American Geophysical Union may be in an ideal position to bring about standardization of this work throughout the country through the activity of its Section of Hydrology. The Federal Bureau of Agricultural Engineering has prepared a manuscript on "Principles and practices of snow-surveying" and it is planned that it will be published as a Government bulletin. It is thought that a report based partly on this proposed Government publication and partly on the experiences in the same work by the United States Weather Bureau in eastern United States might be a worth-while contribution for the Section of Hydrology, American Geophysical Union.

My suggestion arises, of course, from close contact with this one piece of work and I realize that it may constitute a somewhat restricted field of endeavor for a committee of national consequence and broad interests in hydrology. A more general project would undoubtedly be more in line with the purpose of such a committee. I will be very much interested to know what the recommendations of the other members of our Committee are and feel quite sure that among them will be one which will serve better than that which I have suggested.

These suggestions are presented herewith in hope that they will elicit comments and suggestions for the most efficient operation of the Committee from members of the Union. It is anticipated that a definite program of activity for the Committee will be formulated at and immediately following this meeting.

U. S. Soil Conservation Service,
Washington, D. C.

# LIST OF CURRENT PUBLICATIONS TO ACCOMPANY REPORT OF THE COMMITTEE ON SNOW

Carl Elges

The list of current publications on snow and ice has been assembled by the compiler with assistance of others who have generously provided articles and reports. A broad view has been taken of the subject-matter and a fairly complete cross-section of literature in all countries has been sought in order to maintain broad contacts. The entire field of snow and ice has been included together with related precipitation and storms to afford a complete picture of their evolution. Their human relationships also have been stressed. Thus the Committee seeks to perform the functions that have developed with its growth.

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## PAPERS

# THE RELATION OF SUSPENDED TO BED MATERIAL IN RIVERS

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It has been known for some time that if the average concentration of suspended sediment at any point in a wide straight stream was known, the average concentration at any other point could be determined. This was first demonstrated by O'Brien [see 1 of "Bibliography" at end of paper] using the methods developed by Schmidt in a study of turbulence in the atmosphere. That the results obtained with this method agree with actual observations in streams and channels was demonstrated by Christiansen [2] and Richardsen [3]. For artificial turbulence it has been checked by Hurst [4] and Rouse [5].

The relation is of the following general form

$$N = N_a c^{-p\theta} \tag{1}$$

where N = concentration of suspended solids having a velocity of fall (c), $p = c\,U_m/DgS$, $\theta = \int_a^z (dz/\alpha)$, $\alpha = (1 - z)/(dx/dz)$, $z = y/D$, $x = U/U_m$, U = velocity at point, $U_m$ = mean velocity in vertical, and D = depth. The equation relates the suspended-material concentration at any relative distance z above the bottom to the known concentration at some relative distance, a. Using the above nomenclature the so-called exchange-coefficient, $\epsilon$, at any point is equal to $(D^2gS/U_m)\alpha$. The above relation assumes that the unit-shear at the bottom is equal to wDS.

The derivation of equation (1) is given by O'Brien [1] in slightly different form. Since the space available does not permit presenting this subject in full, it is suggested that those wishing a detailed understanding of the relation of suspended material to turbulence study the references given in the bibliography, particularly the first two.

The usefulness of equation (1) is limited by the fact that the suspended-material concentration must be known at some one point before the concentration at any other point can be calculated. It is believed that the composition and concentration of the suspended material is related to the composition of the stream-bed (if composed of non-cohesive material), and to the hydraulic characteristics of the river. The purpose of this paper is to develop these relations. The amount and composition of the material in suspension at the bottom, or very near to the bottom, will be related to the bottom-composition and to the hydraulic factors tending to cause material to be placed in suspension.

In a river where the suspended material is in a condition of equilibrium, that is, when there is no tendency to scour or fill, the average amount of material reaching the bottom is equal to the average amount that is picked up from the bottom. The composition of the bottom may approach the composition of the material in suspension near the bottom, or it also may be coarser than that in suspension. Material is picked up from the river-bottom and kept in suspension by the upward velocity-components of the turbulent eddies. The process is intimately associated with the turbulence-mechanism.

The rate at which material is picked up from the bottom is proportional to the intensity of the vertical velocity-components due to the turbulence-eddies. Experiments [6] have shown that the vertical velocity-components are statistically distributed according to the normal error-law. The equation of this frequency-distribution function is

$$f(v) = (1/\sqrt{2\pi}\sqrt{\overline{v^2}})e^{-v^2/2\overline{v}^2} \tag{2}$$

$$\int_{-\infty}^{\infty} f(v)\,dv = 1 \tag{2a}$$

The quantity [f (v) dv] indicates the proportion of the time that the vertical velocity lies between the magnitudes v and (v + dv). The area under the whole curve (from +∞ to -∞), is, of course, unity. If the root-mean-square value of the vertical velocity, $\sqrt{\overline{v^2}}$, is known, the function f(v) is determined for all values of v.

The material picked up from the bottom must of necessity be dependent also on the composition of the bottom. Therefore, the average rate at which particles of any size are picked up and placed in suspension should be proportional to the relative amount of those particles present in the bottom, to the magnitude of the vertical velocity present capable of picking them up, and to the relative amount of time during which velocities capable of picking up particles of that size exist. It is assumed that a vertical velocity equal to, or greater than, the velocity of settling will tend to place particles in suspension. In the discussion to follow, particles of any size will be characterized by their velocity of fall in still water, c. The relative amount of particles having an average settling velocity of c can be determined from a size-analysis curve of the material at the stream-bottom. For instance, the amount of material having a velocity of fall of $c_1$ or less may be 60 per cent and the amount having a velocity of fall of $c_2$ or less may be 70 per cent. Therefore, the amount that has an average velocity of fall $c = [(c_1 + c_2)/2]$ is equal to (70 - 60) or 10 per cent. Let this relative amount be represented by $\Delta F(c)$.

Expressed mathematically, the average rate at which particles of any size, c, are picked off the bottom is proportional to the following expression

$$\Delta F\ (c) \int_c^{\infty} v f(v)\ dv \tag{3}$$

All values of vertical velocity, v, equal to or greater than c are capable of placing particles, of a size having a velocity of fall of c, in suspension. For the term f(v), equation (2) can be substituted. The quantity $\sqrt{\overline{v^2}}$ is not ordinarily determined or known; therefore, it is necessary to determine to what other known hydraulic factors it is proportional.

In the analysis of turbulent exchange of momentum it has been shown that the unit-shear, at any point is equal to $\rho\,\overline{uv}$, where $\rho$ is the liquid density and $\overline{uv}$ is the mean product of the turbulent velocity-components u and v [7]. The term u is the longitudinal component and v is the transverse component. Since the longitudinal component is in general proportional to the transverse component, the quantity $\overline{uv}$ is proportional to $\overline{v^2}$ near the bottom.

At the stream-bottom let $\sqrt{\overline{v^2}}$ equal $K\sqrt{\tau_0/\rho}$, where $\tau_0$ is the unit bottom-shear and where K is the proportionality-constant. After substituting for f(v) in equation (3) from equation (2) we have

$$\Delta F(c) \int_c^{\infty} (v/\sqrt{2\pi}\,K\sqrt{\tau_0/\rho})e^{-v^2/2K^2\tau_0}\ dv \tag{3a}$$

The value of K has not been experimentally determined; however, there is evidence that points to its being a constant for a general type of turbulent flow, such as for wide-channel flow. Therefore, K and the other constants will be dropped in equation (3a). Then letting $t = v/\sqrt{\tau_0/\rho}$ the following expression may be written

$$\Delta F(c)\sqrt{\tau_0/\rho}\int_{t_c}^{\infty} te^{-t^2}\ dt \tag{4}$$

in which $t_c = c/\sqrt{\tau_0/\rho}$. The term $\rho$ is left in the expression for t in order to make t a dimensionless parameter. It is believed that the parameter, $t_c$, is of fundamental importance in the study of the relation between material in suspension and bottom-composition. The expression within the integral in equation (4) is, of course, solely a function of $t_c$.

Since at the bottom the rate of picking up of sediment must in general equal the rate of dropping, the following proportionality should exist

$$N_s c \propto \Delta F(c)\sqrt{\tau_0/\rho}\int_{t_c}^{\infty} te^{-t^2}\ dt \tag{5}$$

The term $N_s$ is the concentration per unit-volume or in parts per million of sediment in suspension at the bottom of an average size characterized by the settling velocity c. Simplify equation (5) by transferring c to the right side of the proportionality and $\Delta F(c)$ to the left side. We then have

$$N_s/\Delta F(c) \propto P \tag{6}$$

where

$$P = (1/t_c)\int_{t_c}^{\infty} te^{-t^2}\,dt \tag{6a}$$

The function P can be expressed in the form of a series thus

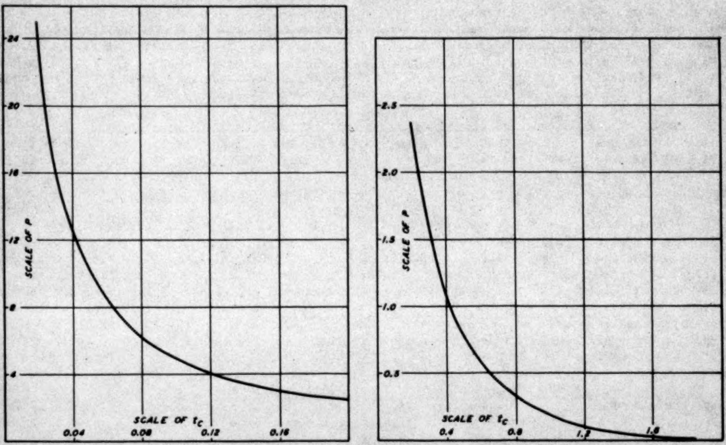

FIG. 1—VARIATION OF PARAMETER $t_c$ WITH FUNCTION P

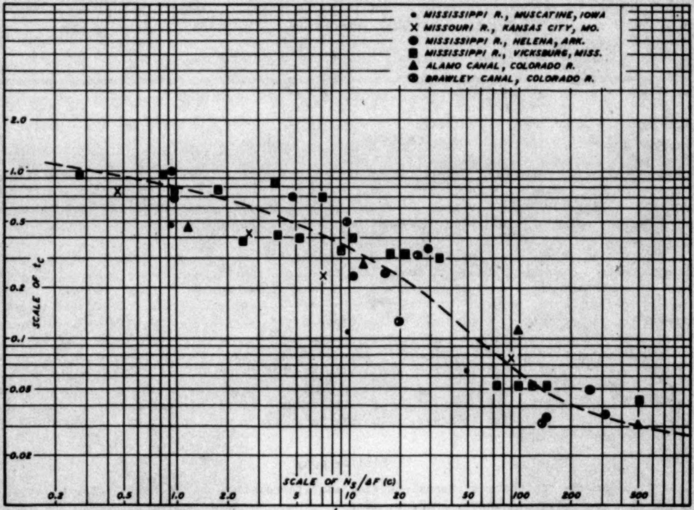

FIG. 2—PLOTTING OF $t_c$ AND $N_s/\Delta F(c)$ AS DETERMINED FROM FIELD-DATA

$$P = (1/2t_c) - (t_c/2) + (t_c^3/4) - (t_c^5/12) + \ldots\ t_c^{2n-3}/2(n-1)! \qquad (6b)$$

A plotting of the function P for various values of $t_c$ is shown in Figure 1. Note that as $t_c$ approaches zero, P approaches infinity, and that P approaches zero rapidly when $t_c$ is greater than unity. This would indicate that sand-sizes giving a value of $t_c$ of one or greater would not be found in suspension in any great quantity. This is an important fact, if true, and has been determined entirely by a mathematical analysis of the problem of how sediment is placed in suspension by turbulence. The approaching of P to infinity as $t_c$ gets very small indicates that for the small sizes of silt no exact relation can be established between the bottom-composition and the material of that size in suspension. In fact, there might be a considerable amount of small-size silt in suspension without a measurable quantity of this material being present in the bottom. Practically speaking, the amount of material in suspension of very small size is dependent on the runoff entering the stream and not on the bottom-composition.

Equations (6) seem to be quite significant; it now remains to obtain experimental data so that the two quantities in this expression, $[N_s/\Delta F(c)]$ and $t_c$, can be calculated and plotted. Since $t_c$ is a function of P, $t_c$ is thus functionally related to $[N_s/\Delta F(c)]$. No laboratory-data exist at present which would permit such an analysis. Also the field-data on actual streams in which all the necessary factors were accurately determined simultaneously are quite scanty.

Use has been made of the data collected on the Imperial Valley of California Canals by Fortier and Blaney [8], on the Lower Mississippi by the engineers of the Mississippi River Commission [9], and on the Missouri River by Dr. L. G. Straub for the Kansas City Division of the United States Engineer Corps. The data for the Upper Mississippi River were collected and analyzed by the authors with the cooperation of the engineers of the Rock Island District and the Cincinnati Division of the United States Engineer Corps. The help received from all of the above organizations is gratefully acknowledged. These data permitted the determination of $[N_s/\Delta F(c)]$ and $t_c$, and a plotting of these data is shown in Figure 2. The quantity $N_s$ is in parts per million and $\Delta F(c)$ is in per cent.

Obviously a great deal of scattering of any field-data is to be expected, particularly since the streams observed may not have been exactly in equilibrium; nevertheless, the existence of the functional relationship as indicated by equation (6) seems to be verified. The upper limit of one for the value of $t_c$ for material in suspension seems to hold. It is also concluded that for practical purposes no very accurate prediction of the value of $N_s$ for values of $t_c$ less than about 0.020 can be expected. Sediment-sizes giving values of $t_c$ less than 0.020 are very likely not to be present in the bed of the stream in measurable quantities.

The equation of the curve that seems to best fit the plotted points has the general form

$$[N_s/\Delta F(c)] = bP^n \qquad (7)$$

where P is the function of $t_c$ as defined in equation (6a). The constants in this equation for the curve plotted in Figure 2 are $b = 5.55$ and $n = 1.61$.

In general, it seems that prediction of suspended-material concentration from a knowledge of the hydraulic characteristics and bottom-composition of a river is quite possible within certain limits. Experimental data from carefully controlled experiments in the laboratory are now needed to more carefully determine the functional relationships pointed out.

In addition to the usefulness of the relationship indicated by equation (6) in predicting suspended-material concentration, it seems that this relationship may be of fundamental importance in the entire problem of channel-bed erosion and sedimentation. For a channel of given slope and depth the minimum size of material which will not be picked up from the bottom and placed in suspension can be determined by the upper limit of the value of $t_c$. Whether any part of the suspended load entering a channel will settle can be determined by calculating $t_c$ and noting if the actual value of $[N_s/\Delta F(c)]$ is greater or less than that given by data such as shown in Figure 2. In other words, if actual conditions are not those of equilibrium, whether erosion or sedimentation will occur, can be determined from the relationship given by equation (6) and shown in Figure 2 which is for conditions of equilibrium. A complete determination of the functional relationship indicated in equation (6) should go far toward providing a fundamental solution of the stable-channel problem.

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# VELOCITY-DISTRIBUTION IN OPEN CHANNELS

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The momentum-transfer theory of turbulent flow as developed by Prandtl [see 1 of "References" at end of paper] and von Kármán [2] has given rise to an equation for the velocity-distribution in circular pipes which agrees well with experimental observations. Attempts to adapt this theory to flow in open channels have been made by O'Brien [3] and Keulegan [4], and others. The following remarks are intended to describe a further attempt along similar lines.

Formulas which give good agreement with observation for both smooth and rough pipes have been derived from the expression [5]

$$(u_m - u)/\sqrt{T_0/\rho} = 1/K \ \ell n \ (r/y) \tag{1}$$

If this equation be written for two points on the same velocity-gradient, there is obtained

$$(u_m - u_1)/\sqrt{T_0/\rho} = 1/K \ \ell n \ (r/y_1)$$

and

$$(u_m - u_2)/\sqrt{T_0/\rho} = 1/K \ \ell n \ (r/y_2)$$

Subtracting

$$(u_2 - u_1)/\sqrt{T_0/\rho} = 5.75 \log (y_2/y_1) \tag{2}$$

In equation (2) K has been given the value 0.40, which has been found to apply to circular pipes.

It is evidently possible to choose two points on a measured velocity-gradient and compute the tractive force on the boundary from equation (2). This equation should apply to any two-dimensional turbulent flow regardless of whether the solid boundary is smooth or rough.

The data of Bazin [6] offer an excellent opportunity to check the applicability of equation (2) to open-channel flow. Sufficient data are given to compute the tractive force from equation (2) at various points on the wetted perimeter. The total traction on the boundary can then be obtained by integrating the unit-values over the solid surface. If the theory is valid, the total traction thus obtained should be found equal to the quantity wAs, which must, in uniform flow, be the frictional drag per unit-length on the channel-bed. Open-channel flow is essentially different from flow in a pipe due to the presence of the free surface. The foregoing would not be expected to apply in a region near the surface, for there the tractive force is presumably zero. The surface is similar to the pipe-center in that respect and, on the other hand, is similar to a solid boundary in that there is no transfer of mass across it. For this reason, the investigation has been confined to a region near the solid boundary.

O'Brien has applied the more complicated expression of von Kármán to velocity-measurements made on the Mississippi, but lacked a positive check on the method because slopes were not given in the data he used. Keulegan has computed the distribution of tractive force from the data of Bazin, starting from the known average value, but did not make the check suggested above.

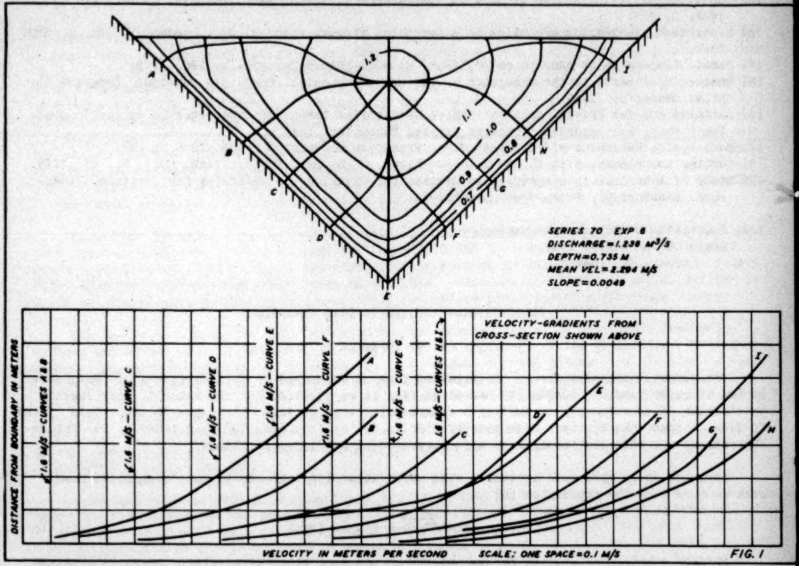

FIG. 1

In order to make this comparison of theory and measurement, the following computational procedure was employed:

(1) Fourteen measurements, including velocity-distributions and slopes, were reproduced from Bazin to a large scale, and lines perpendicular to lines of equal velocity were sketched in as shown in Figure 1.

(2) The lines orthogonal to the velocity-contours were assumed to be analogous to radial lines in a circular pipe, since no shearing stress may arise due to the transfer of mass across them. Values of $T_0$ at the bases of these lines were computed from equation (2), selecting pairs of points near the channel-bed. A typical example is given in Table 1. It is noted that the values of $T$ as computed from different pairs of points on the same line agree quite satisfactorily.

Table 1--Sample computation of $T_0$ from equation (2)

| Curve | $u_2$ | $u_1$ | $y_2$ | $y_1$ | $T_0$ | Average $T_0$ |
|---|---|---|---|---|---|---|
| | m/sec | m/sec | meter | meter | kg/meter$^2$ | kg/meter$^2$ |
| B | 2.10 | 1.80 | 0.075 | 0.033 | 0.223 | |
| | 2.20 | 1.90 | 0.096 | 0.045 | 0.260 | |
| | 2.30 | 2.00 | 0.124 | 0.059 | 0.270 | 0.251 |
| D | 2.00 | 1.80 | 0.060 | 0.028 | 0.115 | |
| | 2.10 | 1.90 | 0.077 | 0.039 | 0.144 | |
| | 2.20 | 1.10 | 0.102 | 0.050 | 0.131 | 0.130 |
| G | 2.00 | 1.70 | 0.046 | 0.020 | 0.216 | |
| | 2.10 | 1.80 | 0.062 | 0.026 | 0.199 | |
| | 2.20 | 1.90 | 0.079 | 0.035 | 0.226 | 0.214 |
| I | 2.10 | 1.80 | 0.165 | 0.054 | 0.120 | |
| | 2.20 | 1.90 | 0.220 | 0.070 | 0.114 | |
| | 2.30 | 2.00 | 0.285 | 0.090 | 0.113 | 0.116 |

(3) The total traction per unit-length of channel was obtained by integrating the unit-values over the solid boundary. This was compared with the known total traction $wAs$. The comparison is given in Table 2.

It is seen that the computed tractions, using $K = 0.4$, do not agree well with the known values. A possible explanation of the discrepancy lies in the fact that K, the so-called universal constant of turbulent flow, was taken at 0.40, the value which has been found valid for circular pipes.

The values of K' which would bring the computed and observed values of $T_0$ into agreement are also shown in Table 2. The variations in K' were plotted as a function of various dimensionless parameters representing the geometry of the cross-section, but no regularity could be discovered. It is to be noted that two triangular sections with the same included angle gives values of K' of 0.32 and 0.37.

Table 2--Comparison of computed and known tractive forces

| Designation (from Bazin) | | Shape | Slope | Computed traction | Known tractions | K' |
|---|---|---|---|---|---|---|
| Series | Exp. | | | | | |
| | | | | kg/meter | kg/meter | |
| 74 | 4 | Semicircular | 0.0015 | 0.234 | 0.0876 | 0.24 |
| 57 | 1 | Rectangular | 0.0049 | 0.818 | 0.412 | 0.28 |
| 70 | 6 | Triangular | 0.0049 | 0.422 | 0.265 | 0.32 |
| 56 | 1 | Rectangular | 0.0049 | 0.542 | 0.357 | 0.32 |
| 63 | 3 | Rectangular | 0.00886 | 0.933 | 0.497 | 0.29 |
| 60 | 2 | Rectangular | 0.00839 | 0.356 | 0.413 | 0.43 |
| 58 | 4 | Rectangular | 0.0015 | 0.261 | 0.131 | 0.28 |
| 69 | 6 | Trapezoidal | 0.0049 | 0.823 | 0.250 | 0.22 |
| 64 | 1 | Rectangular | 0.0015 | 0.205 | 0.145 | 0.37 |
| 72 | 5 | Semicircular | 0.0015 | 0.145 | 0.0922 | 0.32 |
| 76 | 4 | Trapezoidal | 0.000487 | 0.248 | 0.109 | 0.26 |
| 67 | 3 | Rectangular | 0.0043 | 0.330 | 0.167 | 0.28 |
| 69 | 2 | Triangular | 0.0049 | 0.139 | 0.117 | 0.37 |

A complete theory for open channels would make possible the computation of the roughness of the surface at various points on the solid boundary. Computation showed that the ordinary equation for velocity-distribution near the rough surface of a pipe gave erratic results when applied to the channels of Bazin. In spite of the difficulties it is felt that the following conclusions are justified:

(1) The form of equation (2) may be applied to the velocity-distribution near the bed of an open channel, y being measured along a line orthogonal to the lines of equal velocity.

(2) The value of K to be used in equation (2) is not 0.40 but appears to be dependent upon the geometry of the channel, ranging from 0.22 to 0.43 in the cases presented above.

Notation--$u_m$ = maximum velocity in a circular pipe; $u$ = the velocity at a point a distance $y$ from the boundary; $r$ = the radius of a circular pipe; $T_0$ = the unit tractive force at a solid boundary; $\rho$ = mass-density; $K$ = the universal constant of turbulent flow; $w$ = unit-weight of water; $A$ = cross-sectional area of channel; $s$ = slope of the channel-bottom.

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# STUDIES OF MEANDERING OF MODEL-STREAMS

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Introduction--The United States Waterways Experiment Station at Vicksburg, Mississippi, recently conducted a series of tests which were intended to throw light upon the problem of the meandering tendencies of alluvial streams. [These tests are described in full in Tech. Memoranda Nos. 61-1, 61-2, and 61-4 of the Experiment Station.] These tests were conducted in a flume 15 feet wide and 50 feet long (see Figs. 1 and 2). The flume was filled with clean, medium-size sand to a depth of about 1-1/2 feet. In each test, a straight, parabolic-shaped channel was molded through the sand, lengthwise of the flume, with one curve at the upstream end of this channel (see Fig. 3). A constant quantity of water was supplied to the head of the channel, and sand was added to the channel at a uniform rate. A constant over-all slope was maintained by the control of the water-surface elevation in a tailbay at the downstream end of the channel. With only these items of control, the channel was permitted to meander through the sand-bed of the flume.

The general method of development of the meandering channels was very similar to that of typical alluvial streams, and afforded a remarkably accurate rapidly moving small-scale picture of the long-time manner of variation of such streams. In particular the formation of bars, the caving of the opposite banks, the general downstream progression of bends, and the formation of cut-offs and ox-bow lakes were very well illustrated by the developments in the flume. Attention is invited to Figures 4 to 16, in which these phenomena are presented in pictorial form. The development of the meandering channel is described in the following paragraphs.

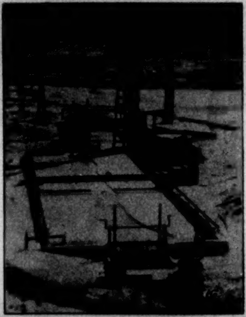
Meander-development--A preliminary test established the fact that an initially straight channel, without any disturbing factors to cause a deflection of the directive force of the water, would remain straight. Therefore, all subsequent tests were made with a short entrance channel molded at an angle of 45° with the axis of the initial parabolic channel (and with the longitudinal axis of the flume).

The molding of an initial bend caused immediate changes in the straight channel. Pictures taken shortly after the tests were started (see Figs. 4 to 7) indicate that a sinuous flow existed in the channel even before the development of bars and pools. The fact that the bars and pools formed almost simultaneously throughout the length of the channel (although with a progressive dampening effect as their distance from the entrance increased) also supports this contention.

The meandering of the channel during the conduct of a test developed in the following manner: The maximum impingement of the current, with resulting scour, occurred in the lower part of the initial bend, against the concave bank. The sand-grains scoured from this bank were moved along the bed to form a bar on the same side of the stream and just below the point of scour. As the bar increased in size and was built out into the stream, a corresponding increase in the size of the pool on the opposite side of the stream was effected, thus starting a bend in the reverse direction. An area of dead water was created on the sheltered (downstream) side of the bar due to the protection of the bar itself (see Fig. 10); the result was that this area did not fill with sand. Inasmuch as similar phenomena occurred almost simultaneously throughout the flume, several bends were developed simultaneously.

As the tests progressed, the continuation of the above action caused a continuous increase in the size of the bends, accompanied by a progressive downstream movement of the bends. Figures 4 to 16 illustrate pictorially the development of the bends during one of the tests of long duration, and Figure 17 illustrates diagrammatically the progressive changes in the location of the thalweg, in one of the shorter tests. In every bend scour occurred on the concave bank, usually in the downstream portion of the bend. The sand eroded from this bank was carried downstream, most of it being deposited on the convex-bank bar on the same side of the stream from which it was eroded; some of the sand, however, was carried still farther downstream, to be deposited either on the crossing bar or on the convex-bank bar immediately downstream therefrom, on the opposite side of the stream.

Soon after the start of a test, there were eight or nine clearly outlined bends. As the test progressed, the bends enlarged and progressed downstream; at the end of a test there were usually four bends remaining within the flume. In the later stages of the tests, cut-offs frequently occurred. One such cut-off can be seen to have taken place between the times of Figure 14 and of Figure 15. These cut-offs were observed to occur usually at times of maximum total length of the channel-thalweg. The length of the thalweg seemed to fluctuate gradually above and below an average value, the curve of its length roughly approximating a sine-curve.



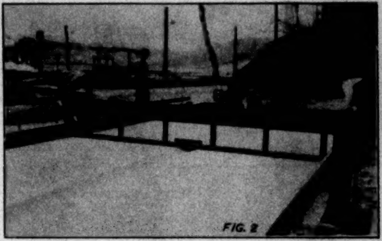


FIG. 2

FIG. 1—GENERAL VIEW OF TESTING FLUME AND APPURTENANCES [PHOTOGRAPHS OF CHANNEL-DEVELOPMENTS TAKEN FROM PLATFORM BETWEEN TREES]

FIG. 2—MOLDING CHANNEL THROUGH SAND, PREPARATORY TO STARTING A TEST

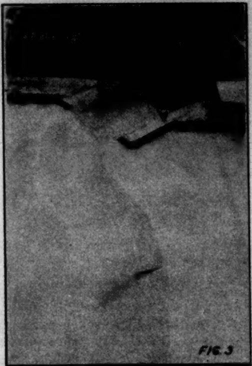
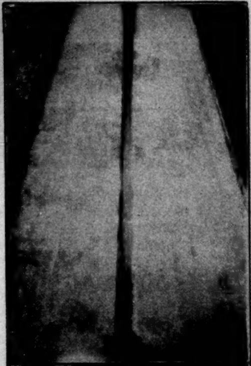
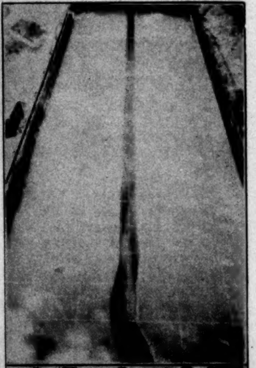
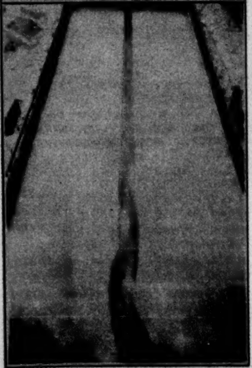
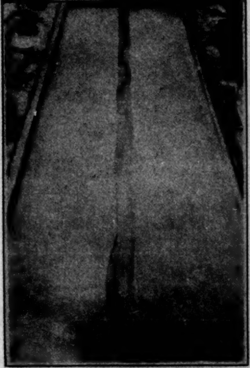


FIG. 3









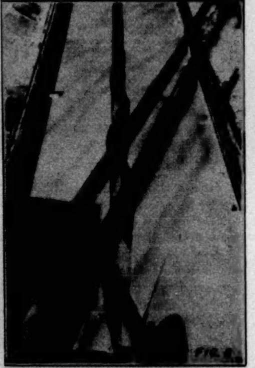
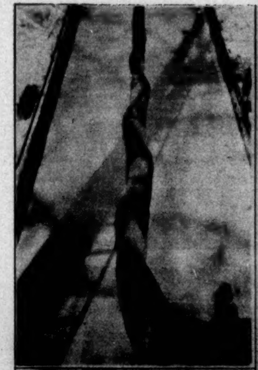
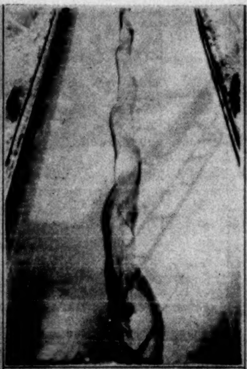
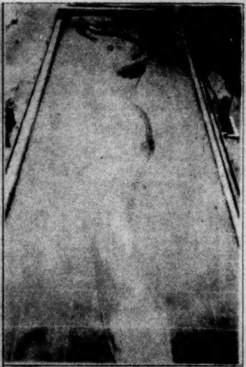


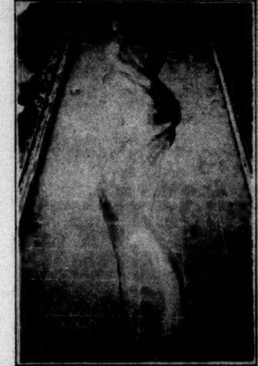
FIG. 8

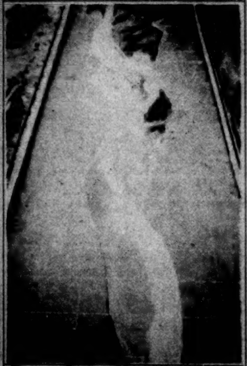
FIG. 3—FIXED ENTRANCE-CHANNEL AND FIRST BEND AS MOLDED IN SAND-BED  FIG. 4—STRAIGHT CHANNEL IMMEDIATELY BEFORE STARTING A TEST; WHITE STRINGS STRETCHED ACROSS FLUME ARE TWO FEET APART  FIG. 5—THIRTY MINUTES AFTER STARTING TEST  FIG. 6—ONE HOUR AFTER STARTING TEST  FIG. 7—ONE AND THREE-QUARTER HOURS AFTER STARTING TEST; NOTE WELL-DEFINED BENDS AND BARS WITHIN STRAIGHT CHANNEL  FIG. 8—TWO HOURS AFTER STARTING TEST

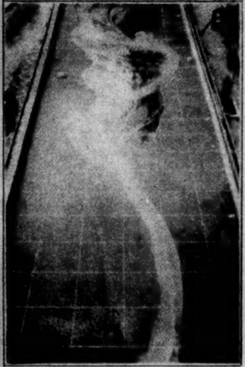


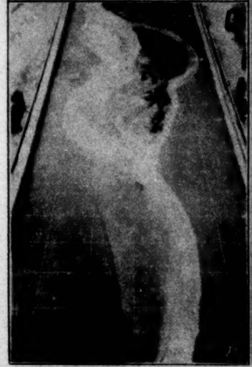












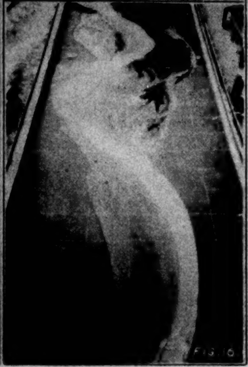


FIG. 9—THREE HOURS AFTER STARTING TEST

FIG. 10—FOUR HOURS AFTER STARTING TEST; BED HAS BEEN DRAINED TO REVEAL BARS, CROSSINGS, AND POOLS

FIG. 11—TWENTY HOURS AFTER STARTING TEST

FIG. 12—THIRTY HOURS AFTER STARTING TEST

FIG. 13—THIRTY-FOUR HOURS AFTER STARTING TEST

FIG. 14—SIXTY-FOUR HOURS AFTER STARTING TEST

FIG. 15—NINETY-FIVE HOURS AFTER STARTING TEST; NOTE CUT-OFF HAS TAKEN PLACE IN INTERVAL BETWEEN TIME OF THIS PHOTOGRAPH AND THAT IN FIGURE 14

FIG. 16—ONE HUNDRED AND THREE HOURS AFTER STARTING TEST

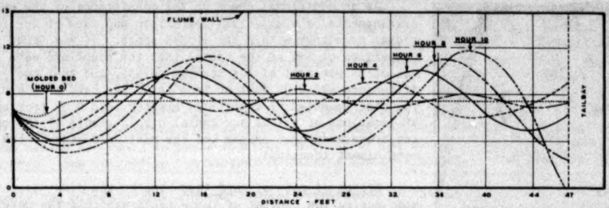


*FIG. 17—PROGRESSIVE CHANGES IN LOCATION OF CHANNEL-THALWEG; THESE CURVES PERTAIN TO A DIFFERENT TEST FROM TEST ILLUSTRATED IN FIGURES 4 TO 16; MORE RAPID DEVELOPMENT OF CHANNEL IN THIS TEST WAS CAUSED BY DIFFERENT CONDITIONS OF DISCHARGE AND RATE OF SAND-INTRODUCTION*

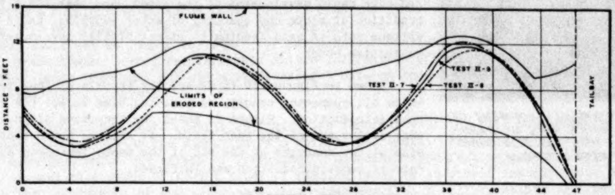


*FIG. 18—LOCATIONS OF CHANNEL-THALWEG AT END OF THREE IDENTICAL TESTS; NOTE REMARKABLE ABILITY OF FLUME TO PRODUCE CONSISTENT RESULTS IN SUCCESSIVE TESTS, WHEN CONDITIONS OF OPERATION WERE KEPT SAME*

Consistency of reproduction--In order to determine the consistency of development of the meandering channel, a series of three tests was conducted under conditions as nearly identical as possible. In all these tests, the channel was molded to the same shape, the quantity of water supplied was the same, the rate and method of supplying sand to the head of the channel was the same, the tailwater-elevation was the same, and the duration of the test was the same.

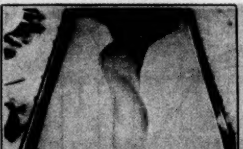


FIG. 19

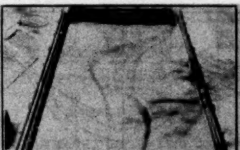


FIG. 20

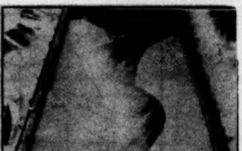


*FIG. 19—FINAL DEVELOPMENT OF TEST IN WHICH NO SAND WAS INTRODUCED AT ENTRANCE FIG. 20—FINAL DEVELOPMENT OF TEST IN WHICH RATE OF SAND-INTRODUCTION WAS 0.05 CUBIC FOOT PER HOUR*
*FIG. 21—FINAL DEVELOPMENT OF TEST IN WHICH RATE OF SAND-INTRODUCTION WAS 0.10 CUBIC FOOT PER HOUR*

The surprising consistency in the results of these tests is shown in Figure 18, in which are plotted the thalwegs of the three channels, and the limits of the eroded areas.

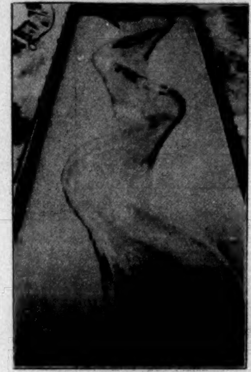


*FIG. 22—FINAL DEVELOPMENT OF TEST IN WHICH RATE OF SAND-INTRODUCTION WAS 0.20 CUBIC FEET PER HOUR*

As an additional check on the consistency of the channel-developments, a statistical comparison was made of the individual soundings within the eroded areas. It was found (in a comparison of two of the tests) that the soundings were identical at 35 per cent of the sounded points, and that the vertical difference was 0.02 foot or less at 90 per cent of the points. The discrepancies of magnitudes greater than 0.02 foot occurred at locations of slight horizontal displacements of the pools; the cross-sectional shapes and the maximum depths of the pools were almost identical.

Effect of rate of sand-feed--One of the first discoveries made during the conduct of these tests was that the development of the channel depended directly upon the manner and rate of introduction of sand at the entrance. In general, it was found that increased rates of sand-introduction resulted in greater and more rapid development of the bends, and that for a given condition of slope and quantity of water supplied, there was an optimum rate of sand-feeding to effect similar developments of successive bends.

Shown in Figures 19 to 22 are the results of four tests in which all operating conditions were the same except the rate of sand-introduction. Figure 23 shows the locations of the thalwegs at the end of the four tests. It will be noted that the size of the meanders at the end of the tests increased as the rate of sand-introduction was increased.

Operation without the introduction of sand at the entrance resulted in the development of a scour-hole at the end of the fixed entrance-section. This condition tended to dampen the deflective force at the entrance, and resulted in subnormal meandering throughout the length of the flume.

Tests made with the introduction of a surplus of bed-load material resulted in excessive development of the first meander--both as to rapidity of formation and as to amplitude. The crossing below the first pool built up correspondingly high and rapidly, making it necessary to build levees on the outside of the pool. This action necessitated the raising of the tailwater in order to maintain the desired slope, and levees became necessary throughout the length of the channel. These levees undoubtedly introduced a surplus of sand in all pools, since they were continuously eroded along with the banks proper, but probably did not greatly affect the general character of the development. Probably because of the much higher tailwater-elevation, the stream did not meander with the same speed at the tailbay as it did for tests with lesser quantities of bed-material introduced.

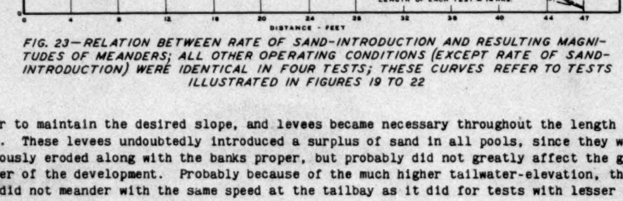


*FIG. 23—RELATION BETWEEN RATE OF SAND-INTRODUCTION AND RESULTING MAGNITUDES OF MEANDERS; ALL OTHER OPERATING CONDITIONS (EXCEPT RATE OF SAND-INTRODUCTION) WERE IDENTICAL IN FOUR TESTS; THESE CURVES REFER TO TESTS ILLUSTRATED IN FIGURES 19 TO 22*

Slope-stabilization--It was noticed in each of the earlier tests that the channel rather quickly assumed an over-all slope of about 0.004 and then fluctuated about that value. To corroborate this observation, a series of tests was made with initial slopes varying from 0.003 to 0.006, other conditions remaining constant. Curves plotted to show the relation between the over-all slope and the total elapsed time indicate an oscillatory tendency of the over-all slope above and below an average value of approximately 0.004. That this slope is an equilibrium value for the specific conditions of discharge, bed- and bank-material, etc., was confirmed by the fact that no meandering of the channel occurred with a molded slope of 0.003, but that meandering did take place as the molded slope was increased to a value greater than 0.004. The optimum sand-feed tests had average slopes of 0.0039.

The slope-oscillation noted above was due to the decrease of over-all slope with the development of greater meander-amplitudes until a point was reached at which the tractive force of the stream became too small to cause continued erosion of the banks; at this point cut-offs usually occurred, thus increasing the slopes and causing new development in the "alluvial valley."

Summary and comments--The sinuous channel-development in the flume in many respects simulated the development of an alluvial river. Pools and crossings developed immediately after operation was begun, and such typical formations as ox-bow lakes (due to the occurrence of cut-offs) were produced in the later stages of the experiment. While this similarity to natural conditions was quite notable, attention is called to the fact that this channel-development resulted from a combination of ideal conditions--a constant flow, through a bed of uniform composition and with no tributaries discharging variable bed-load into the channel. Such conditions, of course, would not be likely to obtain for any considerable length of time in any natural stream. These tests, therefore, furnished little information of direct mathematical applicability to full-scale problems, but did provide general data on the natural meander-tendencies of an uncontrolled fluvial channel.

In addition, these tests clearly indicated the importance of the rate and manner of introducing bed-material during the operation of a movable-bed model. Although these tests did not provide data from which the effect of irregular or haphazard sand-feeding could be determined, it was reasoned that since different rates of feeding resulted in almost instantaneous differences in the development of the first bend, any deviation from a uniform method of sand-introduction would produce similar deleterious effects in the first and succeeding bends.

Acknowledgments--The studies described above were made at the United States Waterways Experiment Station under the direction of Captain (then Lieutenant) F. H. Falkner, then Director of the Experiment Station. William R. Perret was in direct charge of the flume-tests, under the general supervision of Joseph B. Tiffany, Jr. The reports from which this article was prepared (Tech. Mem. Nos. 61-1, 61-2, and 61-4) were prepared by Joseph B. Tiffany, Jr. Lieutenant Paul W. Thompson is now Director of the Experiment Station.

U. S. Waterways Experiment Station,
Vicksburg, Mississippi

## STUDIES OF THE TRANSITION-REGION BETWEEN LAMINAR AND TURBULENT FLOW IN OPEN CHANNELS

Lorenz G. Straub

It is generally recognized in the many fluid-motion occurrences that the flow-conditions vary greatly between the conditions of laminar and complete turbulence. This is, of course, true for flow through pipes, coarse-grained granular materials, and open channels of various types. Considerable importance is attached to such variations in flow. A more or less empirical approach is necessary to define the relation of bulk-velocity of flow to resistance to flow.

In connection with the design of various types of open-channel-flow models to simulate motion-occurrences in nature, a knowledge of this transition-region becomes extremely important if mistakes are not to be made in constructing the model too small for dynamic similarity and if the size of the model is not to be made larger than need be for satisfactory results. It is, of course, desirable economically to construct an open-channel-flow model such as a river-model as small as possible provided a satisfactory degree of dynamic similarity is obtained. With the foregoing application in view as well as the general fundamental study of fluid flow, a series of experiments were started a number of years ago at the University of Minnesota to obtain data regarding the conditions of flow at low velocities. This paper describes one of the earlier series of experiments. The observations here reported were made largely by Edward Silberman, a research assistant. The channel used for this series was of rectangular section, 1.70 inches wide and three inches deep, fabricated of aluminum (diagrammatic sketch of set-up shown in Fig. 1). The experimental set-up was so arranged that fluid could be circulated through the channel with the latter tilted at various slopes. Observations were made of the depth, discharge, and

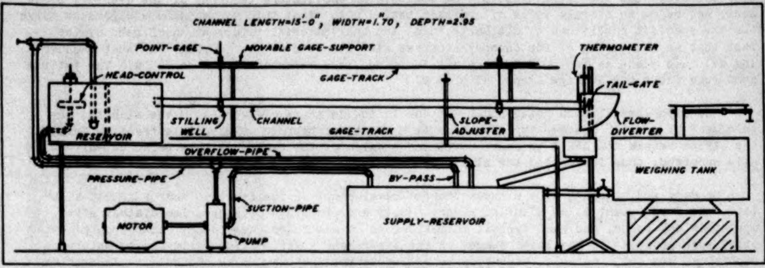

CHANNEL LENGTH=15'-0", WIDTH=1.70", DEPTH=2.95"
POINT-GAGE
MOVABLE GAGE-SUPPORT
HEAD-CONTROL
GAGE-TRACK
THERMOMETER
TAIL-GATE
STILLING WELL
CHANNEL
GAGE-TRACK
SLOPE-ADJUSTER
FLOW-DIVERTER
RESERVOIR
OVERFLOW-PIPE
PRESSURE-PIPE
BY-PASS
WEIGHING TANK
SUCTION-PIPE
MOTOR
PUMP
SUPPLY-RESERVOIR

FIG. 1—DIAGRAMMATIC SKETCH, EXPERIMENTAL SET-UP FOR STUDIES OF TRANSITION-REGION OF FLOW IN OPEN CHANNELS

slope for various depths at uniform flow. As fluid water at various temperatures and also kerosene at various temperatures were used, in all cases a careful check was made of the fluid viscosity by the use of an Ostwald viscosimeter. Depths were measured to the thousandths of an inch. In this report there is presented only a summarized statement of the results with the narrow rectangular channel. Further experiments have been made and are still in progress with channels of different shape and fluids of various viscosities.

A heating system is provided in the supply-reservoir and the fluid temperature is thermostatically controlled. Slopes of channel of 0.001, 0.002, 0.0025, 0.003, 0.004, 0.006, and 0.008 were used successively with kerosene circulated through the channel, and similar slopes were used with water as the fluid medium.

The hydraulic engineer is usually concerned with determining rates of flow by use of empirical formulas, in particular the Chezy formula $V = C\sqrt{RS}$ and the Manning formula

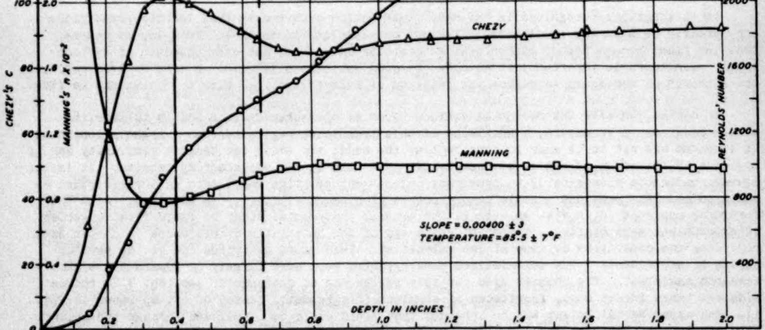


FIG. 2—TYPICAL DATA FOR ONE SLOPE OF CHANNEL SHOWING RELATION OF CHEZY'S C, MANNING'S n, AND REYNOLDS' NUMBER TO DEPTH OF FLOW (SLOPE CONSTANT)

$V = (1.486/n)\ R^{2/3}\ S^{1/2}$. Here V is the mean velocity of flow, R is the hydraulic radius, S is the slope of the gradient, C is an impirical constant, and n is an empirical constant. With these practical formulas in mind the data for the experiments are here analyzed, showing the variation in Chezy's C with depth of flow and Reynolds' number, and also the variation in Manning's n with depth of flow and Reynolds' number. Reynolds' number, Re, was taken as $RV/\nu$, where $\nu$ is the kinematic viscosity of the fluid. Inasmuch as perfect geometrical similarity is not obtained for different depths of flow in the case of a rectangular channel, the values of depth were plotted as abscissas (rather than Reynolds' number as abscissas) with n, C, and Re as ordinates for different slopes of the channel. A typical set of points for one slope is shown in Figure 2. The curves for the various slopes have the same general shape. The values of Chezy's

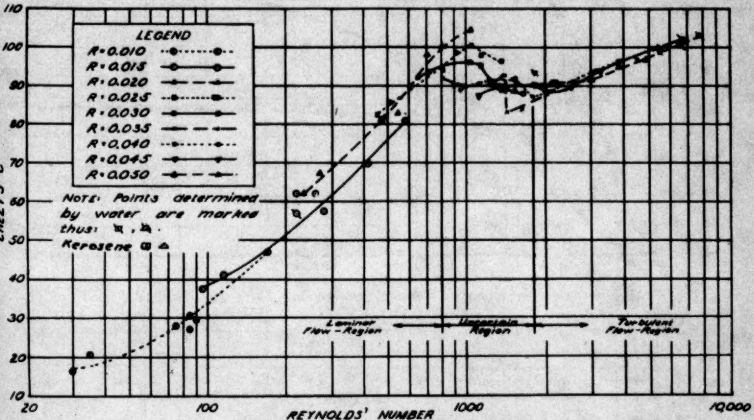


FIG. 3—RELATION OF CHEZY'S C TO REYNOLDS' NUMBER FOR WATER AND KEROSENE USING DIFFERENT SLOPES OF CHANNEL

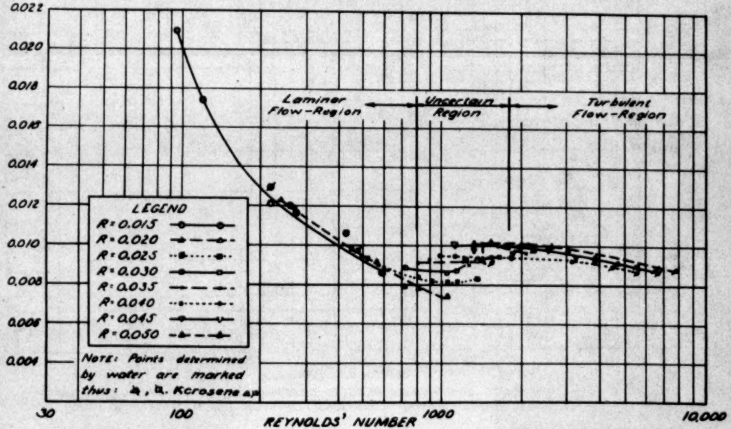


FIG. 4—RELATION OF MANNING'S n TO REYNOLDS' NUMBER FOR WATER AND KEROSENE USING DIFFERENT SLOPES OF CHANNEL

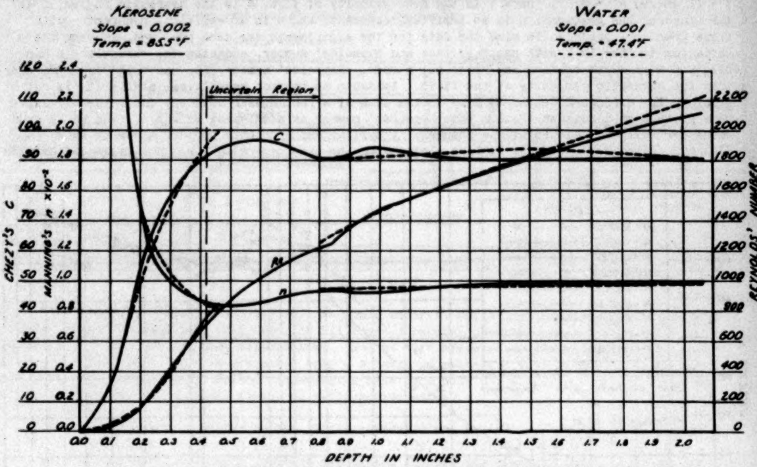


FIG. 5—CURVES SUPERIMPOSED SHOWING DYNAMIC SIMILARITY BETWEEN TWO SERIES OF RUNS WITH KEROSENE AND WATER

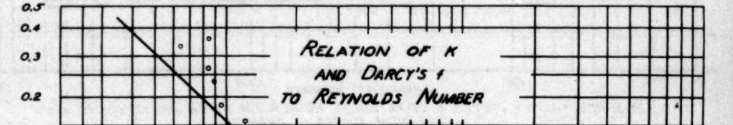


FIG. 6—SUMMARIZED COMPARISON RESULTS OBSERVATIONS OF FLOW THROUGH OPEN CHANNEL WITH CORRESPONDING CONDITIONS FOR FLOW THROUGH SMOOTH PIPE

C increase rapidly in the laminar-flow region to a point near the first occurrence of turbulence. Here the curves break sharply and fall to nearly a constant value in the turbulence-region. Curves of inverse shape are described by the data computed for the n values. For the turbulent region of flow the n value was found to be nearly constant. A summary for all slopes and both fluids is presented in Figures 3 and 4, showing respectively the relation between Chezy's C and Reynolds' number, and the relation between Manning's n and Reynolds' number. Doubtless part of this lack of complete congruence of the curves for different slopes is due to the fact that Reynolds' number for a rectangular channel does not define the condition for complete dynamic similarity for different slopes, inasmuch as geometrical similarity is not obtained. Nevertheless, for these experiments it is evident that using the hydraulic radius as the length-factor in a Reynolds' number gives satisfactory results, despite the fact that geometically the sections compared are not similar.

A further interesting comparison is made by superimposing the curves for two typical series of observations, one for water and one for kerosene (Fig. 5). Although the viscosities were very different, the curves having corresponding ordinates are almost congruent for the two fluids.

Figure 6 presents a summarized comparison of the results of observations of flow through the open channel with corresponding conditions for flow through smooth pipes. The full lines correspond to the curves for flow through pipes below and above the critical velocity, respectively, the hydraulic radius being used here as the length-factor in Reynolds' number. The scattering of points indicating observed values for flow in open channels is doubtless, at least in part, due to the lack of geometrical similarity. Despite this condition, it is evident that the hydraulic radius provides a good average linear dimension to use in Reynolds' number for defining bulk-turbulence. In connection with practical studies of conditions of flow in open channels, such as in the use of hydraulic models, it becomes necessary to deal with approximate average values. It appears from these data that the critical flow-conditions in open channels are defined reasonably well by Reynolds' numbers corresponding to those found by extensive investigations of flow through circular pipes.

The Reynolds' critical value for open channels using the hydraulic radius as the characteristic length seems to be at about 640, possibly lower. The values of C and n, respectively, in the Chezy and Manning formulas are quite definitely dependent upon the Reynolds' number. In the turbulent region the value of n apparently stays quite constant with variations in Reynolds' number. This corresponds quite definitely to observations that have been made in large canals and natural water-courses.

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## SOME EXPERIMENTS ON SHALLOW FLOWS OVER A GRASSED SLOPE

W. O. Ree

Introduction--Investigations into the phenomena of surface-runoff have indicated that there are natural laws which govern the conversion of a part of the rainfall into surface-runoff. Formulas have been developed to explain these processes. However, as is often the case, there is a great need for experimental data to evaluate the coefficients in these formulas. It is the purpose of this paper to present the results of some experiments on very low flows in a grass-lined waterway, and to interpret these results in terms of the equation for overland-flow in the hope of helping fill this need.

The tests on which this discussion is based were made as part of an intensive investigation being conducted by the Soil Conservation Service to determine the hydraulic behavior of vegetal-lined waterways. The evaluation of the equation of overland-flow is an incidental use of the hydraulic data collected.

These tests were conducted at the Spartanburg Outdoor Hydraulic Laboratory of the Soil Conservation Service located near Spartanburg, South Carolina [for a description of this Laboratory, see Civ. Eng., v. 8, No. 10, October, 1938]. This Laboratory is under the technical supervision of H. L. Cook and under the general direction of C. E. Ramser, Head, Section of Watershed and Hydrologic Studies. Dr. M. L. Nichols, as Acting Chief of the Division of Research, administers all research activities of the Soil Conservation Service.

The experiment--The data here discussed were obtained in testing a channel lined with

Bermuda-grass sod. This channel was trapezoidal in cross-section and had a bottom-width of four feet, side slopes of one on one and one-half, and a depth of one and one-half feet. The slope of this channel was approximately three per cent and its length about 50 feet. A stand count of the vegetation showed an average of about 350 stems per square foot. The average length of the stems was 12 inches. At the time of the tests the grass was bent over and formed a loose mat about four inches thick. The soil in the bed of the channel was Cecil clay-loam and was quite firm.

The test-procedure consisted of passing five measured flows down the test-waterway and making all the observations needed to compute the hydraulic elements of the channel. The five tests were made on five successive days and were in the order of increasing magnitude.

The higher rates of flow were measured by means of a calibrated rate-measuring flume which discharged into a forebay so arranged as to permit diversion of the water into a waste-way or into the test-channel. The lowest flows were measured volumetrically. The flow was held steady during the test-periods.

A test-reach ten feet long and located about 20 feet from the upper end of the channel was selected. At each end of the reach a movable point-gage was installed and transverse profiles of the water-surface were made during each test. Cross-sections of the channel bottom at each end of the test-reach were taken immediately before and after each test. All measurements were made to 0.001 foot.

From the measurements taken it was possible to determine the slope, the cross-sectional area, the wetted perimeter, and the hydraulic radius for each test. The values used are the average of the values at the ends of the reach. From these data the mean velocities, and the values of Manning's "n" and Kutter's "n" were computed. The principal hydraulic elements for the five tests are listed in Table 1.

Table 1--Principal elements for tests

| Test | Discharge, Q | Area, A | Mean velocity, V | Wetted perimeter, P | Hydraulic radius, R | Effective slope,* $S_e$ | Manning's n, $n_M$ | Kutter's n, $n_K$ |
|---|---|---|---|---|---|---|---|---|
| | cfs | $ft^2$ | ft/sec | ft | ft | | | |
| 1 | 0.093 | 0.417 | 0.228 | 3.68 | 0.113 | 0.0316 | 0.277 | 0.116 |
| 2 | 0.215 | 0.725 | 0.300 | 4.13 | 0.176 | 0.0318 | 0.280 | 0.131 |
| 3 | 0.356 | 1.003 | 0.356 | 4.41 | 0.227 | 0.0326 | 0.285 | 0.141 |
| 4 | 0.561 | 1.329 | 0.424 | 4.68 | 0.284 | 0.0322 | 0.273 | 0.144 |
| 5 | 0.748 | 1.422 | 0.528 | 4.74 | 0.300 | 0.0314 | 0.224 | 0.124 |

*Slope of energy-line.

During the first four tests the depths of flow were less than the height of the grass-cover. In fact, during these tests the flow was entirely hidden from view. During test 5, however, the flow produced a depth and velocity sufficient to submerge about 30 per cent of the cover. This resulted in a change in the hydraulic characteristics of the test-waterway which is reflected in the sudden drop in the value of $n_K$ and $n_M$.

Derivation of the overland-flow equation--The flow-characteristics in the test-waterway, for the first four tests described above, were similar to those of sheet-flow over a grass-covered slope during a rainstorm. The test-data can, with certain conversions, be used to derive the overland-flow equation for this type of area.

R. E. Horton [Surface runoff phenomena, Part I, Analysis of the hydrograph] has shown that for an area on which overland-flow is taking place the rate of runoff is a function of the average depth of surface-detention and expresses the relation between the two as follows:

$$q = K \delta_a^M \tag{1}$$

where q is the direct surface-runoff rate, $\delta_a$ is the average depth of surface-detention, K is a coefficient depending on the slope and characteristics of the surface, and M is an exponent depending on the degree of turbulence of the flow.

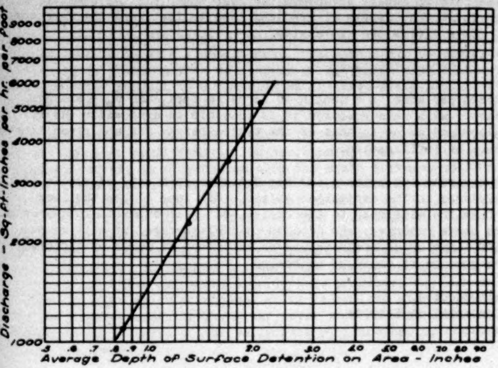
The average depth of surface-detention is used in the overland-flow formula. The depth of flow, however, is not uniform over an area but varies from zero at the watershed to a maximum at the point of outflow, the profile depending on the type of flow. A formula is derived in Dr. Horton's paper for the ratio of the average depth of surface-detention to the depth at the point of outflow. It is given as

$$\delta_a/\delta_c = M/(M + 1) \qquad (2)$$

where $\delta_c$ is the depth at the point of outflow. The depth of flow in the test-channel is the equivalent of the depth of flow at the outlet of an area over which overland-flow is taking place. Therefore, by means of equation (2) the test-data can be expressed in terms of the average detention-depth and in this form they can be used to evaluate the overland-flow equation.

To compute the values of $\delta_a$ by means of equation (2) it was first necessary to determine the value of the exponent M. A preliminary logarithmic plotting was made of the test-data. This plot disclosed that M had a value of almost exactly 5/3, indicating that the flow was practically 100 per cent turbulent. Substituting the values of 5/3 for M in equation (2) and solving for $\delta_a$ resulted in the expression

$$\delta_a = 5/8\ \delta_c \qquad (3)$$



Equation $q_a = 1420\ \delta_a^{5/3}$

FIG. 1—
DISCHARGE - SURFACE DETENTION DEPTH RELATIONSHIP FOR GRASSED AREAS ON 3 % SLOPE

Based on Experiments at the
Spartanburg Outdoor Hydraulic Laboratory
U.S. Department of Agriculture
Soil Conservation Service

For the values of $\delta_c$ the hydraulic radii given in Table 1 were used. The values of $\delta_a$ were then computed by means of equation (3) and listed in Table 2.

Table 2--Values of $\delta_a$ computed by equation (3)

| Test | Discharge, Q | Wetted perimeter, P | Discharge per unit width, $q_b = Q/P$ | Discharge per unit width, $q_a = 43200\ q_b$ | Hydraulic radius, R | Surface-depth at outflow, $\delta_c = 12$ R | Average surface-detention depth $\delta_a = 5/8\ \delta_c$ |
|---|---|---|---|---|---|---|---|
| | cfs | ft | cfs | ft$^2$-in/hr | ft | inch | inch |
| 1 | 0.093 | 3.68 | 0.0253 | 1093 | 0.113 | 1.356 | 0.848 |
| 2 | 0.215 | 4.13 | 0.0521 | 2250 | 0.176 | 2.111 | 1.320 |
| 3 | 0.356 | 4.41 | 0.0807 | 3486 | 0.227 | 2.724 | 1.703 |
| 4 | 0.561 | 4.68 | 0.1199 | 5180 | 0.284 | 3.408 | 2.130 |

The next step was to convert the values of the discharge-rates for the entire width of the test-waterway into discharge-rates per unit of width. For this purpose the wetted perimeter was used as the width; for these tests the two were practically equal. The discharge-rates were then converted from cubic feet per second per foot of width into square-foot-inches per hour per foot of width. These values are also listed in Table 2.

These values of discharge-rates were plotted logarithmically against the corresponding values of average surface-detention depths. This plot is shown on Figure 1. The equation of the straight line is

$$q_a = 1420\ \delta_a^{5/3} \qquad (4)$$

This expression gives the discharge from an area similar in slope and cover to the test-waterway in square-foot-inches per hour per foot of width.

To obtain the equation for the rate of runoff in inches per hour under similar conditions it is necessary to divide equation (4) by the length of overland-flow in feet from the watershed-boundary to the point of outflow. This yields the expression

$$q = (1420/L)\,\delta_a^{5/3} \qquad (5)$$

in which q = rate of runoff in inches per hour, L = length of slope in feet, and $\delta_a$ = average depth of surface-detention in inches. With this equation it is possible to synthesize the hydrograph for an area similar in slope and cover to that of the test-waterway for any given length of slope, rate of rainfall, and rate of infiltration.

The foregoing expression for the relation between surface-detention and rate of runoff is valid only when the assumptions employed in the derivation obtain. For long slopes the flow will not form a continuous sheet from the watershed to the outlet, but will entrench in channels. However, with additional data like those reported, and data on channel-storage, it will be possible to predict the surface-runoff behavior of drainage-basins comprised of areas of different slopes and covers and various arrangements of drainage-channels.

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## EARTH-TIDES SHOWN BY FLUCTUATIONS OF WATER-LEVELS IN WELLS IN NEW MEXICO AND IOWA

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It is quite generally known that ocean-tides produce fluctuations of the water-level in wells of the artesian type located close to the seashore by periodically changing the external load on the aquifer [see 1 of "References" at end of paper]. Fluctuations of ground-water as a result of earth-tides, however, are not generally known although they were observed and studied in a flooded coal-mine in Europe [2] as early as 1879, and later 1905 to 1912 in wells in South Africa [3].

The phenomena of earth-tides first came to the attention of the writer in March, 1938, when studying fluctuations of the water-level in an artesian well near Carlsbad, New Mexico, recorded on charts of a water-stage recorder, which had an approximately semidiurnal period. Because of the distance from the ocean, about 500 miles, and the altitude of the water-bearing formation, about 2700 feet, it appeared that the fluctuations could not be the result of ocean-tides. Neither did it appear they could be the result of other natural phenomena such as changing air-pressure or changes in water-level of a nearby lake and river. There was no pumpage from the aquifer, so the fluctuations of the water could not be caused by pumping. T. M. Cramer, Resident Manager of the United States Potash Company at Carlsbad, New Mexico, suggested that the fluctuations must be the result of some lunar attraction. Further study of the fluctuation was made by Dr. C. V. Theis, of the United States Geological Survey, and the writer, whereby the effect of changing air-pressure was eliminated by correcting the water-levels to an assumed constant atmospheric pressure. In this study it was demonstrated after applying the barometric correction that the remaining fluctuations were fairly regular and progressed with the transit of the Moon. It was also demonstrated that the fluctuations were of the greatest amplitude during the period of new Moon. Further work by W. E. Hale, of the United States Geological Survey, and the writer has shown that the fluctuations were much more regular and of greater amplitude during the periods of new and full Moon than during the first and third quarters. It was, therefore, concluded that they are related to true earth-tides. A preliminary note was published in the Transactions of the American Geophysical Union for 1938 [4].

In March, 1939, a water-stage recorder was installed on a deep well in Iowa City, Iowa, and fluctuations similar to those from the well near Carlsbad, New Mexico, were recorded. As far as is known, these two wells, the flooded coal-mine in Europe, and the boreholes in South Africa, are the only excavations in which fluctuations of ground-water caused by earth-tides have been observed.

There is some reason to believe that fluctuations due to earth-tides have been recorded from time to time by water-stage recorders on wells in this country and doubtless elsewhere, but, because of other and larger fluctuations due to natural or artificial hydrologic causes, the tidal fluctuations were so masked that they have not been recognized. Judging from the New

Mexico and Iowa wells and from the experience of Young [3] in South Africa, the fluctuations are best shown by wells penetrating an artesian aquifer, where the water is under pressure, and where there is no discharge of water from the aquifer by other nearby wells, or if there is discharge that it be at a constant rate. It also seems necessary that the wells be located at a considerable distance from the intake or discharge-area of the aquifer, and from bodies of surface-water subject to a changing water-level which may affect the ground-water head such as oceans, rivers, or lakes.

Discovery of tidal fluctuations in the New Mexican well was incidental to an investigation of ground-water conditions in the surrounding area. Since April, 1937, the United States Geological Survey, in cooperation with the State Engineer of New Mexico, has been making a field-study of the ground-water conditions in the Pecos River Valley, southeast of Carlsbad, Eddy County, New Mexico, for the purpose of determining the source of the contamination of the river-water by salt [5]. In the course of this investigation seven test-wells (see Fig. 1) were drilled for the purpose of obtaining geologic and hydrologic information. With the exception of the first one, the wells were drilled through the Rustler formation and a few feet into the underlying rock-salt of the Salado halite, both of Permian age. A strong sodium-chloride brine-horizon, in which the brine was under considerable pressure, was encountered at the base of the Rustler formation. The wells were cased so as to exclude all but the strong sodium-chloride brine. Periodic measurements of the water-level were made in each well as soon as it was completed. Measurements in three of the wells were supplemented by the installation of automatic water-stage recorders.

The three wells equipped with automatic water-stage recorders were designated as USGS No.1

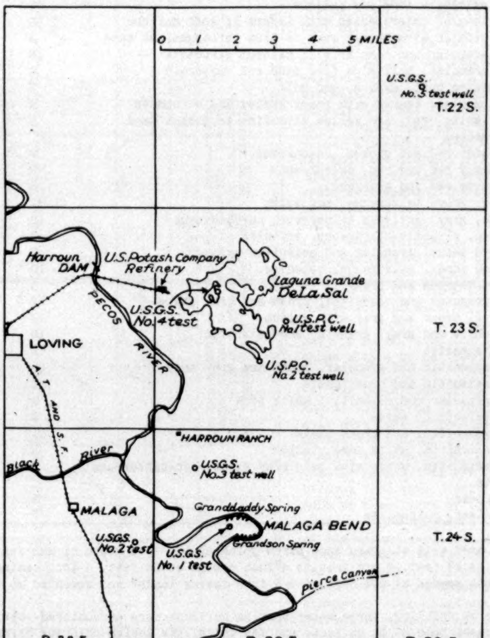
0 1 2 3 4 5 MILES
U.S.G.S. No. 5 test well
T.22 S.
Harroun DAM
U.S.Potash Company Refinery
Laguna Grande De La Sal
PECOS RIVER
U.S.G.S. No. 4 test
U.S.P.C. No.1 test well
LOVING
U.S.P.C. No.2 test well
T. 23 S.
A T AND S. F.
HARROUN RANCH
Black River
U.S.G.S. No.3 test well
MALAGA
Granddaddy Spring
MALAGA BEND
Grandson Spring
U.S.G.S. No.2 test
U.S.G.S. No. 1 test
T.24 S.
Pierce Canyon
R.28 E.
R.29 E.
R.30 E.

FIG. 1—MAP SHOWING LOCATION OF TEST-WELLS IN VICINITY OF LAGUNA GRANDE DE LA SAL, NEW MEXICO

Test, USGS No. 4 Test, and USGS No. 5 Test, respectively. Semidiurnal fluctuations were observed in each of the wells, but in only USGS No. 4 Test were they definitely sharp and pronounced.

This well (Fig. 1) is located about 6-1/2 miles north of the Malaga Bend and 2-1/2 miles east of the Pecos River. It is in the SW 1/4, NE 1/4, Sec. 17, T. 23, S., R. 29E., New Mexico, principal meridian, on a peninsula in Laguna Grande de la Sal, at Latitude 32° 18' 30" north and longitude 104° 00' 10" west. The hole appears to be well outside of the influence of the discharge-area.

Drilling operations on this well began on February 8, 1938, and the well was completed on March 6, 1938. It was drilled to a depth of 286 feet (10 feet into the Salado halite) and then plugged back to about 270 feet with mud and cement. The log of the well given in Table 1 shows the kinds of formations penetrated and their thickness. The descriptions, considerably condensed, are by W. B. Lang [5, appendix] of the Geological Survey.

Table 1--Log of USGS No. 4 Test, altitude 2955.70 feet

| Description | Thickness feet | Depth feet |
|---|---|---|
| Recent | | |
| Silt, brown | 6 | 0-6 |
| Lake fill, etc. | | |
| Gypsum, fine, white | 3 | 6-9 |
| Caliche, extremely fine, soft, white | 7 | 9-16 |
| Gypsum, extremely fine and caliche | 3 | 16-19 |
| Gypsum, tabular interspersed with layers of soft caliche | 13 | 19-32 |
| Gypsum, tabular with 20 per cent calcium carbonate and sand | 3 | 32-35 |
| Gypsum, granular and tabular with calcium carbonate | 16 | 35-51 |
| Gypsum, granular, buff with fine sand and carbonate | 4 | 51-55 |
| Sand, reddish buff, gypsum, and silt | 3 | 55-58 |
| Gypsum, tabular, coarse with sandy shale, and carbonate | 2 | 58-60 |
| Caliche, white, red, and yellow with fine to medium sand | 8 | 60-68 |
| Rustler formation | | |
| Shale, sandy red and gypsum, calcareous | 2 | 68-70 |
| Shale, sandy red and red, calcareous | 9 | 70-79 |
| Shale, sandy red and greyish | 6 | 79-85 |
| Siltstone, gray, calcareous, magnesian | 31 | 85-116 |
| Siltstone, gray, actively calcareous, carbonaceous | 10 | 116-126 |
| Shale, red, slightly calcareous, selenite | 6 | 126-132 |
| Shale, red sandy, granular and selenitic gypsum | 7 | 132-139 |
| Shale, red sandy, calcareous, selenite | 10 | 139-149 |
| Selenite, fibrous and platy | 5 | 149-154 |
| Gypsum, granular and selenitic, brown and gray shale | 12 | 154-166 |
| Shale, red, brown and gray with gypsum | 16 | 166-182 |
| Gypsum, white and gray, granular and selenitic | 18 | 182-200 |
| Gypsum, selenitic | 6 | 200-206 |
| Gypsum, selenitic and granular, brown and gray shale | 14 | 206-220 |
| Gypsum, selenitic and brown shale | 16 | 220-236 |
| Gypsum, granular and selenitic, white pink | 8 | 236-244 |
| Gypsum, selenitic, white | 6 | 244-250 |
| Gypsum, selenitic, and brown shale | 11 | 250-261 |
| Gypsum, selenitic, white some pinkish | 8 | 261-269 |
| Gypsum, selenitic, white with pale gray shale, non-calcareous | 5 | 269-274 |
| Salado halite | | |
| Halite, clear | 5 | 274-279 |
| Halite, clear, polyhalite | 7 | 279-286 |

The well is cased with standard iron screw-joint casing to a depth of 226 feet as follows: 6 5/8-inch casing to 63 feet, 6 5/8-inch to 4-inch swedge at 63 feet, 4-inch casing to 218 feet, 4-inch to 6 5/8-inch swedge at 218 feet, 6 5/8-inch casing landed and cemented at 226 feet.

In the course of drilling, three water-bearing horizons were encountered--the first from 11 to 50 feet, the second from 60 to 68 feet, and the third, the sodium-chloride brine-horizon, from 242 to 273 feet. The brine rose about 196 feet above the point it was encountered or to within 46 feet of the land-surface. This brine is a nearly saturated solution of sodium chloride, having a specific gravity of 1.20.

A Stevens type F, eight-day, water-stage recorder was installed on March 10, 1938, and has been in continuous operation since that time. This instrument has a natural height-scale and a time-scale of 20 hours equal to one inch. The recorder appears to be free from mechanical difficulties and reasonably sensitive. A shallow well, 30 feet deep, was drilled near the deep well, and was cased with 4-inch casing. This shallow well was also equipped with a water-stage recorder in order to obtain a record of the water-levels in the water-bearing bed encountered between 11 and 50 feet.

The hydrograph of the brine-level in the test-well for the first 40 days after the water-stage recorder was installed, from March 10 to April 19, is shown by the middle curve in Figure 2. Comparison of changes in air-pressure, which are read hourly on a mercurial barometer at the United States Potash Company Refinery, 1.75 miles west of the well, with fluctuations of water-level in the well for this period indicate that the barometric fluctuations of water-level amount to a little less than 70 per cent of that of a barometer with a fluid density of 1.20. However, comparisons in later hydrographs by W. E. Hale seem to indicate a somewhat lower efficiency. In order that the changes in air-pressure and the changes in water-level in the well could be compared, the barometric readings were converted from inches of mercury to feet of water having a fluid density of 1.20, and a barometric efficiency of 70 per cent was applied. The curve thus obtained is shown by the bottom line on Figure 2. In Figure 3 are shown the corresponding curves for the same well for the period October 1 to 31. On this Figure the barometric curve, computed by W. E. Hale, is shown with a 60 per cent efficiency.

An inspection of the barometric curves and of the curves of the water-level in the well show that in general the two sets of curves are similar in their major fluctuations. A close study, however, reveals that in detail they are dissimilar. It is evident from this dissimilarity that there must be some force or forces other than changes in air-pressure causing fluctuation of the water-level. In order to study the other force or forces more closely the effect of changing air-pressure was eliminated by correcting the water-levels to a constant barometer. For simplicity in order that the correction would be all in one direction, a pressure was selected below which it was not probable the barometer would fall. The pressure used for the water-level curve obtained in March and April, 1938, was 26.48

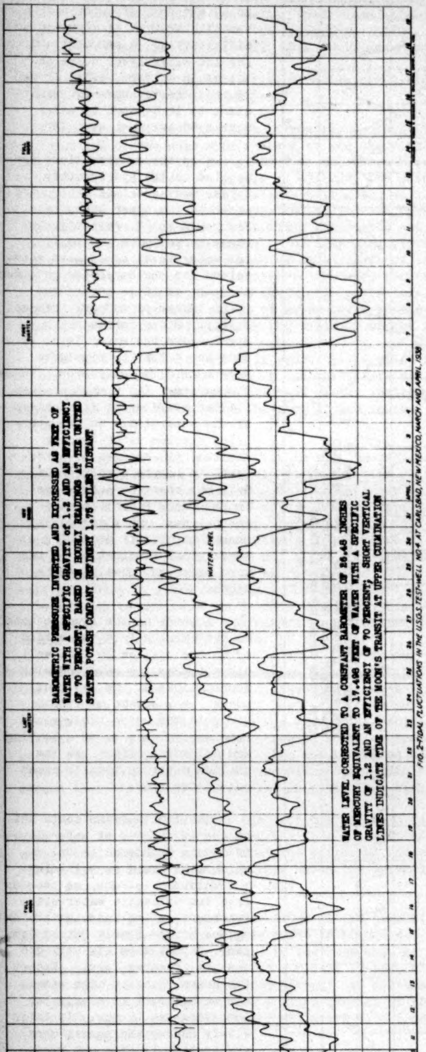

FIG. 2-TIDAL FLUCTUATIONS IN THE U.S.G.S. TEST-WELL NO.4 AT CARLSBAD, NEW MEXICO, MARCH AND APRIL, 1938

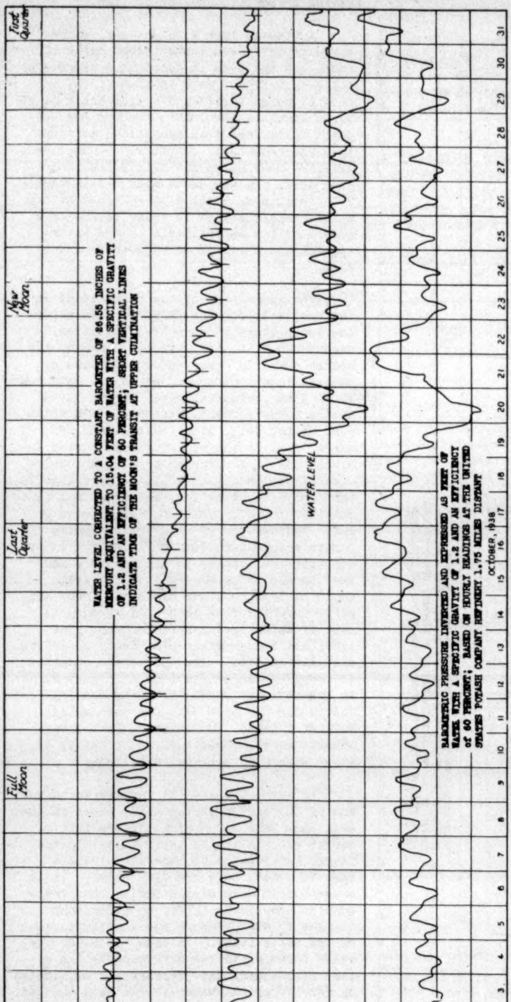

FIG. 3—TIDAL FLUCTUATIONS IN THE U.S.G.S. TEST-WELL NO 4 AT CARLSBAD, NEW MEXICO, OCTOBER, 1938

inches of mercury, equivalent to 17.498 feet of water with a specific gravity of 1.20 and an efficiency of 70 per cent and for the water-level curve obtained in October, 1938, it was 26.55 inches of mercury, equivalent to 15.04 feet of water with a 60 per cent efficiency.

When these corrections were applied to the hydrographs, curves were obtained, which are shown as the upper lines in Figures 2 and 3, respectively. These curves show the position the water-level would have maintained had the barometer remained constant at 26.48 inches and 26.55 inches of mercury, respectively. Other forces which might cause the water-level in USGS No. 4 Test to fluctuate were carefully considered. These forces are: (1) A more-or-less similar semidiurnal fluctuation of the water-table in the overlying shallow water-bearing horizon; (2) changes of water-level in Laguna Grande de la Sal; (3) changing water-level in the Pecos River; and (4) earth-tides. Only one cause seemed capable of producing a semidiurnal fluctuation of the kind observed, namely, earth-tides.

A study of the fluctuations of hydrographs from the recorder on the shallow 30-foot well did not show any relation with fluctuations of the residual curve. Any effect of fluctuations in the water-table would necessarily have to be a loading and unloading effect, as the shallow water is tightly cased out of the well.

The fluctuations could not be due to changes of water-level in Laguna Grande de la Sal, which also would be a loading and unloading effect, as records from two automatic water-stage recorders on the Lake, maintained by the United States Potash Company, do not show any periodic changes of water-level. Except for heavy rains or high winds the water-level is nearly the same from day to day. It falls slowly during the summer when evaporation is high and rises slowly during the winter when evaporation is low.

It is not possible that the semidiurnal fluctuations could be due to loading and unloading effects caused by changes of water-level in the Pecos River. At its nearest point, the Pecos River is 2-1/2 miles from the well. Power-regulation at Carlsbad, about 15 miles upstream, produces a diurnal fluctuation in the river-flow. Thus, if changes of water in the River were the cause of fluctuations in the well, they would occur only once daily.

Thus through the process of elimination earth-tides remain as the only force capable of producing the semidiurnal fluctuations.

In USGS No. 1 Test the lack of sharply defined fluctuations was apparently due primarily to the location of the well with respect to the discharge-area of the brine-horizon. This well (Fig. 1), located in the Malaga Bend of the Pecos River, is surrounded on three sides by the river-channel in which two groups of springs, the Grandson and Granddaddy spring-areas, discharge brine from the brine horizon. When drilling the well it was found that the confining bed of the brine-horizon was thin and incompetent to prevent upward percolation of the brine. As a result, the water-level in the well is largely controlled and the fluctuations dampened by the upward percolation and spring-discharge. The dampening of the fluctuations is probably due in part to rapid transmission of back pressure, as a result of changes in barometric pressure, from the spring-orifices through the aquifer to the well and in part to a change in the rate of discharge of the springs with a change in the static water-level of the aquifer. The water-level in the well is also affected by change of water-level in the river and by changes in position of the water-table due to irrigation in the vicinity of the well.

In USGS No. 5 Test, which is about 12-1/2 miles north and east of the Malaga Bend, the lack of sharply defined fluctuations on the charts are believed to be largely mechanical. The water-level is about 150 feet below the base of the instrument and the difficulty may be due to friction of the float or cable on the side of the casing, or to the frictional resistance of the instrument.

Although the well at Iowa City is much deeper than the USGS No. 4 well near Carlsbad, New Mexico, and penetrates an entirely different kind of rock-formation, the semidiurnal fluctuations in the former are quite similar. This well, which is owned by the State University and is known as the No. 5 well, was equipped with a Stevens Type F, 8-day, water-stage recorder on March 3, 1939, and has been in continuous operation since that time. The well is located about 50 feet from the east bank of the Iowa River, on the north side of Burlington Street, in the SW-1/4, SW-1/4, Sec. 10, T. 79 N., R. 6 W., fifth principal meridian, at latitude 41° 39' 30" north and longitude 91° 32' 25" west. It was drilled in 1927 to a depth of 840 feet. In the log of the well [6] which is given in Table 2, the assignment of formations is by W. H. Norton. "A 10-inch pipe extends to 499 feet; an 8-inch pipe, from this point to the bottom, is perforated at the water-beds. Flowing water was struck in the Galena limestone at 755 feet, with a natural discharge of 100 gallons per minute."

The well through the cooperation of A. A. Smith, Superintendent of Grounds and Buildings of the University, was adapted to accommodate a water-stage recorder by shutting off all flow, and tapping into the casing about 12 feet below land-surface with a two-inch pipe, which was carried through a tunnel underground to the University heating-plant, on the south side of Burlington Street. Here a riser-pipe was attached which extended to the second floor of the plant. At this point the diameter of the riser-pipe was increased to seven inches and was extended about 7-1/2 feet above the floor, or about two feet higher than the static water-level. The altitude of the second floor is 662.43 feet, which is eight feet higher than the land-surface at the well.

For the past five years the well has not been in use, but discharged water through a two-inch pipe into the River. After the flow was shut off and the recorder was installed, the water-level began to recover from the effect of the continuous five-year discharge. The recovery-period lasted about 21 days, during which the water-level recovered about 1.8 feet, 0.95 foot of which occurred in the first ten days.

The hydrograph of the water-level in the Iowa City well for a 28-day period, March 13 to April 10, is shown by the middle curve in Figure 4. A comparison of changes in air-pressure with fluctuations of the water-level, in the same way, as for the Carlsbad well, indicated that the fluctuations amounted to about 75 per cent of that of a barometer with a fluid density of 1.00. Barometric readings were obtained through the courtesy of the United States Weather Bureau from barograms at the Weather Bureau Station located at the airport, 1-1/8 miles south. The readings of the barogram are checked every six hours with a mercurial barometer and the necessary corrections are applied.

Table 2--Driller's Log of No. 5 Well, State University of Iowa

| Description | Depth feet |
|---|---|
| Pleistocene and Recent (50 feet thick; top 654 feet above sea-level) | |
| Soil and clay | 0-15 |
| Sand | 15-50 |
| Devonian limestones and shales (155 feet thick; top 604 feet above sea-level) | |
| Sandy limestone | 50-60 |
| Limestone | 60-95 |
| Broken lime rock | 95-105 |
| Limestone; water, 25 gallons per minute | 105-128 |
| Shale | 128-136 |
| Lime | 136-164 |
| Shale | 164-172 |
| Lime | 172-179 |
| Shale | 179-185 |
| Limestone | 185-201 |
| Shale | 201-205 |
| Niagara limestone (155 feet thick; top 449 feet above sea-level) | |
| Lime | 205-250 |
| Lime | 250-360 |
| Maquoketa shale (193 feet thick; top 294 feet above sea-level) | |
| Shale | 360-390 |
| Lime | 390-406 |
| Shale | 406-432 |
| Lime; more water | 432-465 |
| Shale | 465-478 |
| Lime | 478-499 |
| Lime | 499-504 |
| Shale | 504-553 |
| Galena and Platteville (287 feet thick; top 101 feet above sea-level) | |
| Lime | 553-563 |
| Sand rock | 563-568 |
| Lime rock | 568-580 |
| Shale | 580-585 |
| Lime | 585-755 |
| Magnesia lime; more water | 755-770 |
| Magnesia lime | 770-812 |
| Hard lime | 812-828 |
| Green mud (Glenwood shale of some reports ?) | 828-835 |
| Mud, blue (Glenwood shale of some reports ?) | 835-840 |

The effect of changing air-pressures on the water-levels of this well was also eliminated by correcting to a constant barometer. The pressure used was 28.47 inches of mercury, equivalent to 24.20 feet of water using an efficiency of 75 per cent. As far as could be learned there are no wells within a radius of ten miles in which there is withdrawal of water from the Galena limestone which is the water-bearing formation penetrated by the observation-well. A study of the hydrograph from the water-stage recorder of the United States Geological Survey gaging-station on the River, about 250 feet downstream from the well, indicated there was little if any effect on the water-level in the well from a change in river-stage. There is no shallow well in which changes in the water-table can be observed, but, as the stage of the River controls the position of the water-table, little if any effect on the water-level in the well can be produced by a changing water-table. Thus the situation is similar to that of the Carlsbad well in that earth-tides appear to be the only force capable of producing the semidiurnal fluctuations.

Two sets of curves were selected for the Carlsbad well in order to show that the semidiurnal fluctuations are present the year round and are not dependent upon some seasonal or hydrologic condition. In March and April, 1938, the changes in air-pressure were quite large and irregular, and the water-level was slowly rising. In October, 1938, the reverse condition prevailed. Changes in air-pressure were mostly small and occurred regularly each day, and the water-level was declining slowly. Two other residual curves prepared by W. E. Hale, for September, 1938, and January, 1939, show the same semidiurnal fluctuations.

In the curve for the Iowa City well (Fig. 4), it will be noted that there is a sustained rise of the water-level from March 13 to about March 24. This is due to the recovery of the water-level as a result of the five-year period of flow.

It will be noted on all three of the residual curves that the peaks and troughs of the semidiurnal fluctuations occur a little later each day. As the Moon in its apparent movement around the Earth crosses the meridian at any place approximately 50 minutes later each day on the average, the tide likewise should come approximately 50 minutes later each day. The difference between the length of the lunar day and the solar day is known as retardation in the time of the Moon's transit, and the term retardation may likewise be applied to the difference in the time at which a given phase of the tide arrives as compared to solar time.

In the period March 11 to 18 (Fig. 2), the average retardation of the two daily peaks of the residual water-level curve in the Carlsbad well is 41 minutes per day; in the period March 27

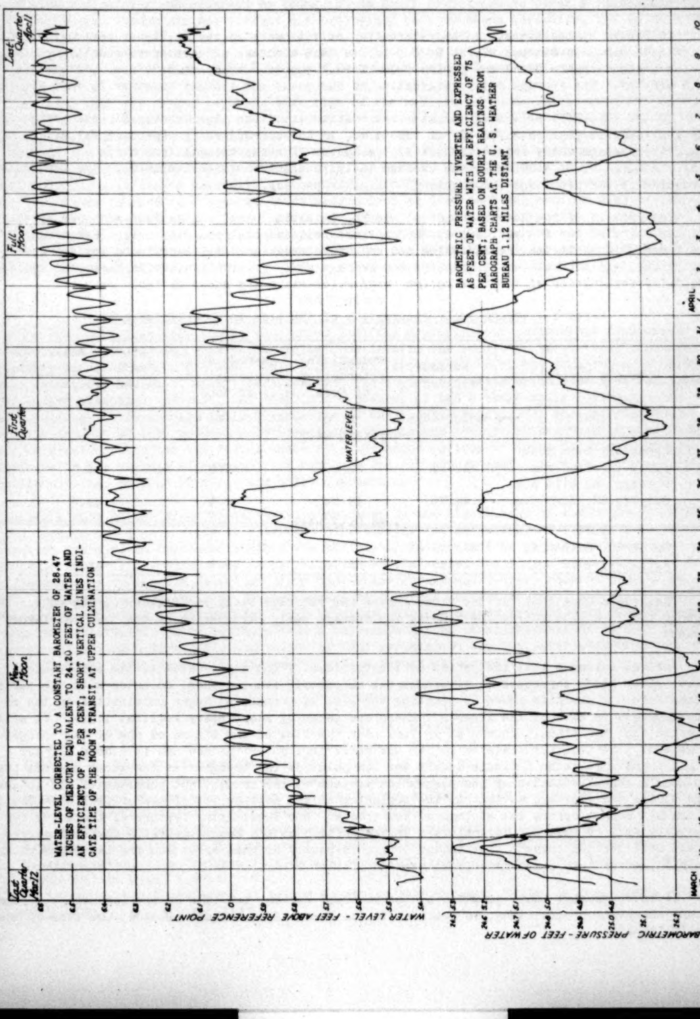

FIG 4—TIDAL FLUCTUATIONS IN THE UNIVERSITY OF IOWA NO.5 WELL AT IOWA CITY, IOWA, MARCH AND APRIL, 1939

to April 4, it is 45 minutes; and in the period April 10 to 18, it is 30 minutes. As the residual curve is prepared by correcting to a constant barometer at hourly intervals, the error in determining the exact point of inflection of a peak or trough may be as much as an hour. By using the longest period possible the percentage-error in computing the average daily retardation will be small. Between the first well-defined peak, on March 11 at 3:00 a.m., and the corresponding last well-defined peak on April 18, at 9:00 a.m., there is an accumulated retardation of 30 hours in the 38.25-day period, or a daily retardation of 47.1 minutes. Similarly, using the first well-defined trough on March 11, at 9:00 p.m., and the corresponding trough on April 18, at 1:00 a.m., there is an accumulated retardation of 28 hours in the 37.17-day period, or a daily retardation of 45.5 minutes. The average daily retardation of the peaks and troughs is 46.3 minutes.

In Figure 3, the average daily retardation of the peaks in the 22.71-day period from October 5, at 4:00 a.m., to October 27, at 9:00 p.m., is 44.9 minutes; and the average daily retardation of the troughs in the 28.67-day period from 11:00 a.m., October 5, to 3:00 a.m., October 28, is 42.3 minutes. The average daily retardation of the peaks and troughs together is 43.6 minutes.

In the Iowa City well (Fig. 4), the retardation is of the same order. For the period from the well-defined peak on March 15, at 5:00 a.m., to the corresponding peak on April 8, at 10:00 p.m., the average daily retardation is 41.3 minutes. For the troughs from March 15, at 9:00 a.m., to April 9, at 4:00 a.m., the average daily retardation is 46.3 minutes. The average retardation of the peaks and troughs is 43.8 minutes per day.

The transit of the Moon's center at upper culmination based on the 1938 and 1939 Ephemeris [7] was computed for the meridian at the Carlsbad well and the Iowa City well. For comparison the times of transit for the beginning and end of retardation, the approximate periods used in the curves, the accumulated retardation and average daily retardation of the Moon, and the average daily retardation of the tide in the observation-wells are shown by Table 3.

Table 3--Average daily retardation of the tide in observation-wells

| Moon's transit | Period elapsed | Accumulated retardation of Moon | Average daily retardation of Moon | Average daily retardation of peaks and troughs of tide in well |
|---|---|---|---|---|
| 1938 | solar days | h m | m | m |
| | | Carlsbad Well | | |
| March 11, 8:35 p.m. | | | | |
| April 18, 2:44 p.m. | 37.76 | 30 09 | 47.9 | 46.3 |
| October 5, 9:16 p.m. | | | | |
| October 27, 3:20 p.m. | 22.75 | 18 04 | 47.6 | 43.6 |
| | | Iowa City Well | | |
| 1939 | | | | |
| March 15, 8:16 a.m. | | | | |
| April 9, 4:32 a.m. | 24.85 | 20 16 | 48.9 | 43.8 |

These data show that for the three curves the recorded daily retardation agrees rather closely and is approximately the same as the average daily retardation of the Moon for these periods.

Further evidence that the period of fluctuations of the water-level in the observation-wells, after being corrected to eliminate the barometric fluctuations, coincide with the period of the Moon's transit is shown by plotting the time of transit at upper culmination on the residual curves in each of the figures. These are shown by short heavy vertical lines. It will be noted that the transit occurs at or very near the time of the minima of one of the troughs. In general, the tendency seems to be, in the early periods of the new and full Moon for the Moon's transit to occur a little before the low point of the trough. As the lunar periods progress the Moon's transit catches up and passes the minimum of the trough, but subsequently it apparently lags during the quarters so that at the beginning of the next period of new or full Moon the time of transit occurs before the minimum of the trough. One outstanding feature of the curve for the Iowa City well is that for several days in the periods of the Moon's quarters there is only a single well-defined trough. The second trough is poorly defined or it and the two peaks of the lunar day merge into a poorly-defined peak.

It is noteworthy that, as shown by the residual curves, the time of the low water, or trough in the observation-well tides, in contrast to the ocean-tides, occurs about at the time of the Moon's transit.

From the two residual curves of the Carlsbad well (Figs. 2 and 3) and one from the Iowa City well (Fig. 4), it is evident that the periods when the semidiurnal fluctuations occur most regularly and are of greatest amplitude, coincide with the periods of new and full Moon. It is also evident that the periods of smallest and most irregular fluctuations coincide with the periods of the first and third quarters of the Moon. It is at times of new and full Moon that the tide-producing forces of the Moon and Sun are acting in the same direction. High tide, then, in the ocean, rises higher and low tide falls lower than the average. When the Moon is in the first and third quarters, the tide-producing forces of the Moon and Sun are opposed and the tide does not rise as high or fall as low as on the average.

The same condition was observed by Young [3] in South Africa and is clearly shown by Plate IV of his report. Young did not correct his hydrograph to a constant barometer, yet in discussing the curve he says [p. 82]: "The semidiurnal fluctuations of level in Borehole No. V attain a maximum amplitude about the times of new Moon and full Moon, and attain a minimum amplitude about the times of the Moon's quadratures." Young also mentions their "wonderful regularity."

In order that the reader may have some idea of the well in which Young observed the tidal phenomena, a brief description of it is given. The well was six inches in diameter, was 65 feet deep, and was situated more than 160 miles from the coast, at an altitude of over 2700 feet above sea-level. The well penetrated a series of northward dipping shales and sandstones, but the character of the particular water-bearing bed is not stated. The series is cut by dolerite dikes and sills. The well flowed naturally at the surface and Young observed by volumetric measurements the change in rate of discharge which ranged from 40.0 to 56.6 gallons per minute; subsequently he determined changes of water-level in the well by manual measurements by the use of a home-made water-stage recorder which was apparently quite accurate. During the period of observation the well was flowing into a nearby tank, so the water-level observed by him does not represent true static level.

## Conclusions

The data presented lead to the conclusion that the approximately semidiurnal fluctuation of the water-levels in the two observation-wells described is the result of earth-tides produced by the attraction of the Moon and Sun. This conclusion is based on: (1) The occurrence of approximately two daily cycles of water-level fluctuations in the two wells which come about 50 minutes later each day as does the Moon; (2) the close agreement of the average daily retardation of these cycles with the average daily retardation of the Moon's transit; (3) the coincidence of the daily troughs in the residual water-level curves with the transit of the Moon at upper and lower culmination; and (4) the faithfulness with which the periods of large regular fluctuations coincide with the periods of new and full Moon and the periods of small irregular fluctuations coincide with the periods of first and third quarters.

Future work on the study of earth-tides as shown by the fluctuation of water-levels in wells should include a critical study to determine more closely the efficiency of the wells as water-barometers and also to determine whether the efficiency is constant or varies with seasonal or hydrologic conditions. This study should involve periods of several years. In order to study the fluctuations in greater detail a larger time-scale in the water-stage recorder should be used. Instead of a time-scale of 20 hours equal to one inch, a time-scale of ten hours or even five hours to one inch is recommended. Air-pressure readings should be available oftener than at one-hour intervals. It is believed that a barograph having chart-graduations of 0.02 inch of pressure and having a time-scale equivalent to that recommended for the water-stage recorder will be satisfactory, if it is checked frequently with a mercurial barometer.

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# FLUCTUATIONS IN ARTESIAN PRESSURE PRODUCED BY PASSING RAILROAD-TRAINS AS SHOWN IN A WELL ON LONG ISLAND, NEW YORK

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Perhaps one of the chief interests of ground-water hydrologists is the study of water-level fluctuations. Since the beginning of the science of hydrology attempts have been made to interpret these phenomena and determine their significance. On the basis of actual observations and "with special reference to Long Island, New York," Veatch [see 1 of "References" at end of paper] in 1906 considered in some detail several different causes of water-level fluctuations. He placed the known causes under two general headings, natural and human. However, considering proximate rather than ultimate causes a further classification might be, and indeed often is, made with regard to the conditions under which the fluctuations are produced by a given agency, natural or human. Thus we speak of "water-table conditions" and "artesian conditions," realizing, however, that the distinction between the two is not always definite. The phenomena peculiar to artesian conditions are usually the result merely of the imperviousness of the confining beds relative to the particular aquifer under consideration. Indeed, it is recognized that perhaps even the most dense clay is not absolutely impervious to the flow of water, given a difference in head, sufficient to produce the flow, though it may be beyond the precision of the means now employed to detect the flow of water through such impervious strata.

In general, water-level fluctuations observed under artesian conditions may be divided into two groups, those occurring while the load on the aquifer remains constant and which are due to various other causes, and those resulting from actual variations in the load on the aquifer. In the first group are those fluctuations caused by variations in the head in areas of recharge or discharge and those caused by pumping from wells.

Variations in the load on artesian aquifers may be comparatively wide-spread in some cases and subject to varying degrees of restriction in others. Thus the second group mentioned above includes fluctuations of varying magnitude and duration depending on the extent, intensity, and rate of variation of the load. Perhaps the best example of a wide-spread and uniform load which is subject to more or less periodic variation is the atmospheric pressure. Variations in atmospheric pressure produce so-called "barometric fluctuations."

Fluctuations are produced by more restricted loading arising from such natural agencies as erosion and deposition and from variations in the level of streams, lakes, or other bodies of water overlying artesian aquifers, and also from such human agencies as buildings and other structures, and, lastly, railroad-trains. Thus, according to the classification proposed here this paper is concerned primarily with fluctuations produced under artesian conditions by a particular type of restricted variable load.

In the work of King [2] referred to by Veatch [1] is a description of water-level fluctuations produced by freight-trains passing a six-inch well which was about 140 feet from the railroad at Madison, Wisconsin. This is doubtless the earliest mention of this phenomenon appearing in American scientific literature. The well in question was 40 feet deep and penetrated three feet of sandstone which was presumably overlain by 37 feet of unconsolidated material. As a loaded freight-train slowly passed the well there was produced "a rapid but gradual rise of the water, . . . followed by only a slightly less rapid fall to the normal level." Veatch remarks that "it is not clear that the water is under artesian head." However, it is now generally conceded that artesian conditions are necessary to produce fluctuations of the type and magnitude observed here.

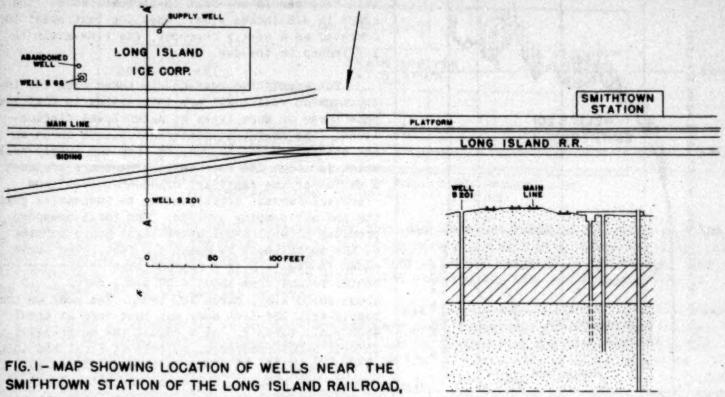

FIG. 1 - MAP SHOWING LOCATION OF WELLS NEAR THE SMITHTOWN STATION OF THE LONG ISLAND RAILROAD, AND SECTION PERPENDICULAR TO THE TRACKS

Observations were begun on an abandoned well of the Long Island Railroad on April 15, 1937. This well, known as Well S-201, is located 54 feet north of the main line of the Port Jefferson branch of the Long Island Railroad and about 360 feet east of the Smithtown Station, as shown on the map in Figure 1. It is eight inches in diameter at the surface and is 89 feet deep. The water-level is 35 to 40 feet below the surface. Unfortunately the log of the well is not available. Information regarding the area and position of the screen is also lacking. However, there is available the log of a nearby abandoned well, Well S-66, which is 110 feet to the southeast of Well S-201 and is on the property of the Long Island Ice Corporation on the opposite side of the tracks. The log [3] of this well as given by the driller, Mr. Emil Lorentson, is as follows:

| Material | Thickness in feet | Depth in feet |
|---|---|---|
| Sand, fine, brown | 40 | 40 |
| Clay, brownish | 30 | 70 |
| Gravel | 30 | 100 |

The section shown in Figure 1 is based on this log. According to the statement of the driller the same general conditions were encountered in other wells drilled in the vicinity of Smithtown. The thickness of the gravel underlying the clay is not definitely known, nor is the extent of the confining layer. This is the Gardiners clay, which is generally quite extensive on Long Island but which is lacking in some places owing to erosion which took place prior to the deposition of the overlying material. The fact that the water-level in Well S-201 fluctuates in response to variations in atmospheric pressure indicates that at least in the immediate vicinity of the well the confining layer is continuous. However, the low "barometric efficiency" of this well, to be considered presently, indicates that at a point some distance from the well the confining layer may be absent.

In addition to Well S-66 there are two other wells on the property of the Long Island Ice Corporation, one of which is abandoned and the other is used as a supply-well and for cooling purposes in the manufacture of ice. The supply-well is reported to be ten inches in diameter and 142 feet deep with a 20-foot strainer between 122 and 142 feet. It is equipped with a multistage turbine-pump with a capacity of 300 gallons a minute.

On April 15, 1937, a Stevens "Type-F" water-stage recorder was installed on Well S-201 with a seven-inch float. Since then, except for occasional short interruptions when intensive studies were being made, this instrument has been in continuous operation on a weekly basis with a natural gage-height scale. This recorder is of the conventional horizontal-drum type, in which the drum is rotated by a float attached to a flexible beaded cable which passes over a grooved

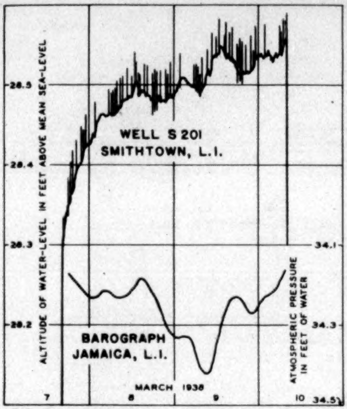

FIG. 2—INSTRUMENTAL RECORD OF WATER-LEVEL IN WELL S-201 AND BAROGRAPH FOR MARCH 7-10, 1938

wheel or pulley geared to the drum. The drum on this recorder is one foot in circumference. The chart is 9.6 inches wide. When the instrument is operated as a weekly recorder, the time-scale is 1.2 inches to the day.

The weekly recorder-charts taken from the instrument on Well S-201 are interesting in that they show three or more types of water-level fluctuations. The most prominent fluctuations shown on the charts are due to pumping from the supply-well, which is about 134 feet away. There are produced a series of the familiar "drawdown-curves" and "recovery-curves" corresponding to successive pumping and non-pumping periods. The total drawdown produced in Well S-201 after eight hours pumping of the supply-well is about 1.0 foot. The curve shown in Figure 2 is a reproduction of the instrumental record from about 4:00 p.m., March 7, to about 10:00 a.m., March 10, 1938. The pump on the supply-well 134 feet away was shut down at about 4:00 p.m., March 7. As a result the water-level in Well S-201 recovered, rapidly at first and then more gradually. At about 10:00 a.m., March 10, pumping was resumed, whereupon the water-level declined.

Superimposed upon the fluctuations due to pumping are those produced by the passing railroad-trains. These fluctuations are of such small magnitude and of such short duration, however, that they appear merely as vertical lines on the chart, and when the water-level is rising or falling quite rapidly in response to pumpage they are often obliterated. In addition there are fluctuations of longer period due to variations in atmospheric pressure as seen by comparing the record from the water-stage recorder with the barograph-record which is plotted on an inverted scale below the water-level curve. By comparing the instrumental record for the period October 22 to November 19, 1938, with the inverted barograph for the same period, it was found that the "barometric efficiency" of Well S-201 is about 20 per cent, that is, the water-level in the well rises 0.2 foot in response to a drop in atmospheric pressure equivalent to a head of one foot of water.

Except where there is a simultaneous fluctuation due to some other cause, such as pumping, it is possible, from the known times of arrival and departure of the various trains, to check each train and determine the magnitude of the fluctuation which it produces. From a study of the recorder-record for March 8, 9, 11, 15, and 18, 1938, it was found that the west-bound trains produced fluctuations ranging from 0.024 to 0.035 foot and averaging 0.030 foot, whereas the east-bound trains produced fluctuations ranging from 0.036 to 0.054 foot and averaging 0.045 foot. Other things being equal, the magnitude of the water-level fluctuations should depend on the weight and the velocity of the trains passing the well. As far as is known, except perhaps on special occasions, the trains have from three to eight coaches each. Two types of locomotives are used on the passenger-trains, one weighing about 237,000 pounds and the other about 309,000 pounds including coal and water. The passenger-coaches average in weight about 110,000 pounds. Each week-day there are 11 east-bound and 11 west-bound trains. Inasmuch as each east-bound train returns within a few hours as a west-bound train, the average weights of east-bound and west-bound trains must be equal over a period of one day or a number of days. This being the case, the observed differences in average water-level fluctuations--0.045 foot for the east-bound and 0.030 foot for the west-bound trains--may be ascribed to differences in the average velocity of the respective trains.

According to observations made April 23, 1937, it is estimated that the east-bound trains pass the well with an average velocity of about 20 feet a second, whereas the west-bound trains have a velocity of 40 or 50 feet a second as they pass the well. The station-platform is a few hundred feet to the west of the well. Thus, west-bound trains may pass the well before appreciably decreasing their speed, whereas east-bound trains doubtless pass the well before attaining their normal speed.

There is apparently a certain velocity at which a train of a given length and weight will produce the greatest fluctuation. If the train passes the well at a lower velocity, the confined

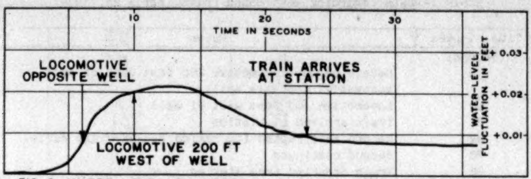

FIG. 3—WATER-LEVEL FLUCTUATION IN WELL S-201 PRODUCED BY WESTBOUND TRAIN, $12^h12^m$ P.M., APRIL 23, 1937

water is given more time to escape laterally and thus dissipate the pressure before it is built up to its full value. On the other hand, if the train passes the well at a higher velocity, the strata overlying the aquifer are not given as much time to become adjusted to the varying load at the surface. Consequently, the load is distributed over a wider area and the intensity of the increased load on the aquifer is less.

Well S-66 is clogged and it is therefore unlikely that it responds to the passing trains. However, it was found that the other abandoned well on the property of the Long Island Ice Corporation does exhibit fluctuations due to the passing trains. This well is eight inches in diameter and sounds 112 feet deep. On March 23, 1938, a Stevens "Type-F" recorder was installed with a seven-inch float and a 1 to 1 gage-height ratio. It was operated on a weekly basis until April 20, 1938. The fluctuations produced by the passing railroad-trains are apparent on the weekly recorder-charts, but they are of much smaller magnitude than those observed in Well S-201. From a study of the instrumental record for April 12, 1938, it was found that nine east-bound trains produced average fluctuations of 0.006 foot and that nine west-bound trains produced average fluctuations of only 0.004 foot. The same trains produced in Well S-201 average fluctuations of 0.046 and 0.030 foot, respectively. Well S-201 is 54 feet from the center-line of the tracks. The 112-foot well is 52 feet from the center-line and on the opposite side of the tracks. When use of this well was discontinued some time ago, the pump-cylinder and check-valve were left in it. This accounts for the sevenfold or eightfold reduction in the magnitude of the water-level fluctuations produced by the passing trains.

More detailed observations of the effect of passing railroad-trains on the water-level in the Smithtown well were begun April 23, 1937, by M. L. Brashears and the writer. In order to magnify the water-level fluctuations in Well S-201 the regular float-wheel was replaced by a special wooden pulley about 1-1/8 inches in diameter giving a gage-height ratio of about 5.1 to 1. And in order to enlarge the time-scale so that the fluctuations might more easily be studied the clock on the recorder was replaced by a special clock which gave a time-scale of about five seconds to the inch. As the recorder-chart was only 9.6 inches long, the maximum continuous time of travel of the pen was only about 48 seconds. If additional record was desired, it was necessary to rewind the pen-carriage cable. About 30 seconds time was required for this operation.

On April 23 observations were made on three west-bound and two east-bound trains. The curve shown in Figure 3 is a reproduction of the first part of the instrumental record obtained during the arrival and departure of the 12:12 p.m. west-bound train, which consisted of a locomotive and three coaches. Data regarding the position of this train at various intervals of time are given in Table 1.

It is seen from Figure 3 that as the train approached from the east the effect did not become appreciable until the locomotive was within 100 or 200 feet of the well. As the locomotive

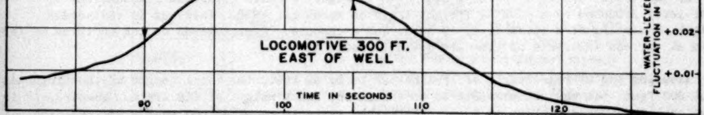

FIG. 4—WATER-LEVEL FLUCTUATION IN WELL S-201 PRODUCED BY EASTBOUND TRAIN, $1^h04^m$ P.M., APRIL 23, 1937

Table 1--Data regarding west-bound train, April 23, 1937

| Time elapsed | Notes |
|---|---|
| seconds | |
| 0 | Record begun; locomotive 300 feet east of well |
| 6 | Locomotive opposite well |
| 10 | Locomotive 200 feet west of well |
| 23 | Train arrived at station |
| 36 | Record interrupted (to rewind pen-carriage cable) |
| 70 | Record continued |
| 85 | Train departed from station |
| 95 | Record ended |

passed the well the rise became quite abrupt. The water-level reached a maximum shortly after the approximate center of gravity of the train passed the well. (The train was about 300 feet in length and passed the well with an estimated velocity of 50 feet a second.) The decline in the water-level as the train arrived at the station and stood opposite the platform was more gradual than the rise produced by the same train as it approached and passed the well. No additional fluctuation occurred as the train left the station, the second part of the curve being merely a continuation of the first part.

The curve given in Figure 4 is a reproduction of the second part of the record obtained during the passage of the 1:04 p.m. east-bound train after the pen-carriage cable had been rewound. Observations on the position of this train, which consisted of a locomotive and four cars, are given in Table 2.

Table 2--Data regarding east-bound train, April 23, 1937

| Time elapsed | Notes |
|---|---|
| Seconds | |
| 0 | Record begun |
| 42 | Record interrupted |
| 46 | Train arrived at station |
| 75 | Train departed from station |
| 81 | Record continued (after rewinding pen-carriage cable) |
| 90 | Locomotive opposite well |
| 105 | Locomotive 300 feet east of well |
| 128 | Record ended |

As the train approached the well from the west, after leaving the station, the rate of rise of the water-level increased continuously and reached a maximum shortly after the locomotive passed the well. The water-level reached its maximum height about 99 seconds after the beginning of the record. The decline in the water-level as the train continued eastward beyond the well was more gradual than the preceding rise. As seen by comparing Figures 3 and 4, both the rate of rise and the rate of decline were less for the east-bound train than for the west-bound train. However, the magnitude of fluctuation produced by the east-bound train was greater than that produced by the west-bound train. These differences are ascribed mainly to the difference in the velocity of the two trains, as previously discussed.

Observations were resumed in March, 1938, the water-stage recorder having been maintained in continuous operation on a weekly basis during the interim. In the series of observations which followed a second special clock was used which moved the recording pen eight inches in 30 minutes. This was a spring-driven clock similar to the type with which the recorder was originally equipped, but which had been converted into a weight-driven clock. Using this clock and the special float pulley described above, observations were made on regularly scheduled east-bound and west-bound passenger-trains as well as on three freight-trains.

Of particular interest is the graph shown in Figure 5 which shows the fluctuations in water-level produced by a passing freight-train on March 21, 1938. This was an east-bound freight consisting of a locomotive, 19 cars, and a caboose. Observations on the position of the train at various intervals of time are given in Table 3.

Assuming the average length of freight-car to be 42 feet, the total length of the train was about 900 feet. It was not possible to ascertain the exact weight of the train. However, it is known that the average weight of freight-cars when empty is about 45,000 pounds and that the

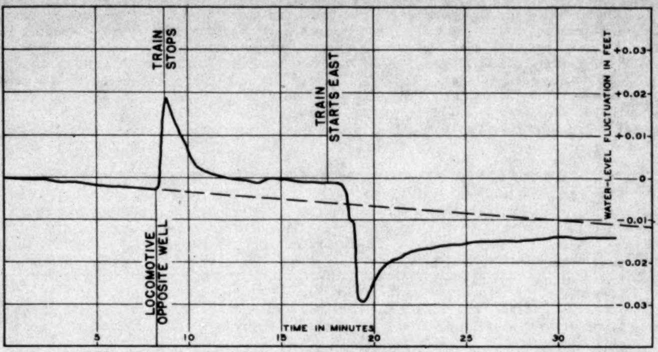

FIG. 5—WATER-LEVEL FLUCTUATION IN WELL S-201 PRODUCED BY EASTBOUND FREIGHT TRAIN, MARCH 21, 1938

Table 3--Data regarding east-bound train, March 31, 1938

| Elapsed time m | Elapsed time sec | Notes |
|---|---|---|
| 0 | 0 | Record begun (3:04 p.m.) |
| 8 | 10 | Locomotive opposite east end of platform |
| 8 | 15 | Locomotive opposite well |
| 8 | 45 | Train stopped, locomotive and 8 cars to east of well |
| 9 | 15 | Locomotive and four cars detached from front end of train; one car switched to siding |
| 13 | 45 | Locomotive and three cars recoupled to train |
| 17 | 30 | Train started east |
| 18 | 45 | Caboose at switch |
| 33 | 00 | Record ended |

locomotive, of type 2-8-0, weighs about 250,000 pounds. Thus the total weight of train when empty would be about 1,150,000 pounds, or about 1280 pounds for each foot of length. Not infrequently the live-load on freight-trains exceeds twice the dead-load. It seems reasonable, therefore, to assume that in this case the live-load at least equalled the dead-load. Thus the weight of loaded train was possibly 2500 pounds for each foot of length.

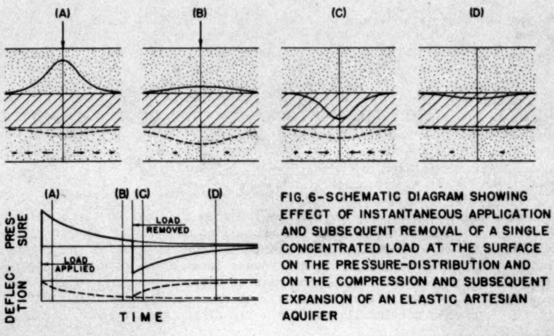

FIG. 6-SCHEMATIC DIAGRAM SHOWING EFFECT OF INSTANTANEOUS APPLICATION AND SUBSEQUENT REMOVAL OF A SINGLE CONCENTRATED LOAD AT THE SURFACE ON THE PRESSURE-DISTRIBUTION AND ON THE COMPRESSION AND SUBSEQUENT EXPANSION OF AN ELASTIC ARTESIAN AQUIFER

As indicated by the initial rate of decline of the curve in Figure 5, the water-level fluctuations produced by the passing freight-train are superimposed on a general downward trend of the magnitude of about 0.02 foot an hour. As the train approached from the west no appreciable effect was observed until the locomotive was nearly opposite the well, whereupon the water-level rose quite abruptly, reaching a maximum of 0.022 foot in about 30 seconds. The maximum occurred shortly after the train had stopped, the locomotive and eight cars then being to the east of the well. Thereafter the water-level gradually declined. In the meantime the locomotive and four cars were "cut" from the front of the train and one of the cars was switched to the siding on the opposite side of the tracks. As the locomotive and the three cars were recoupled to the train a slight rise occurred in the water-level.

The train started east 17 minutes and 30 seconds after the beginning of the instrumental record. As the train left the vicinity of the well a decline in water-level occurred which was comparable both in magnitude and in duration to the rise produced as the same train arrived opposite the well. The rate of decline of the water-level did not become appreciable until nearly all of the train had passed the well. Indeed the maximum rate of decline occurred after the caboose passed the switch 350 feet east of the well. The water-level reached a minimum of 0.023 foot, that is, 0.023 foot below the broken line in Figure 5. Subsequently the water-level recovered, rapidly at first and then more gradually, and approached the level which it otherwise might have had, as indicated on the diagram by the broken line, which is a continuation of the general trend of the water-level in the well before the arrival of the train.

In order to visualize more clearly the effect of the freight-train, the moving load of the train may be considered to be replaced by a load equivalent in lateral extent, which is fixed in position opposite the well, and which varies in magnitude in such a manner as to produce the same effect in the well as that actually produced by the train. This procedure seems justifiable in view of the fact that the time that elapsed between the first noticeable effect as the train approached the well and the stopping of the train opposite the well was small compared to the rate of demise of the pressure-disturbance produced by the train. To simplify matters further, this varying distributed load may be replaced by a single concentrated load which is applied instantaneously, maintained at a constant value for a period of time, and then removed instantaneously.

The diagrams in Figure 6 are intended to indicate, schematically at least, the effect of such a load on the pressure-distribution within an elastic artesian aquifer and on the compression and subsequent expansion of the aquifer following removal of the load. The diagrams A, B, C, and D show the distribution of pressure and the deflection of the upper surface of the aquifer at the respective times indicated on the time-pressure and time-deflection curves. The hydrostatic pressure in the aquifer is plotted as a full line, the upper limit of the confining layer arbitrarily being adopted as a base. The deflection-curve for the upper surface of the aquifer is plotted as a dashed line. (The lower surface of the aquifer is assumed fixed.) These quantities are, of course, grossly exaggerated and are obviously plotted to quite different scales. The lengths of the arrows indicate the relative magnitude of the velocity of flow at various distances from the load. The lower diagram in Figure 6 shows, by the heavy full line, the change in pressure produced by the load, and, by the heavy dashed line, the deflection of the upper surface of the aquifer, plotted against time.

Inasmuch as the load is applied instantaneously, the initial adjustment in the fraction of the load borne by the confined water and that borne by the solid material of the aquifer may also be considered to occur instantaneously. As a result the hydrostatic pressure rises instantaneously to its maximum value at any point a given distance from the load. Thereafter, the pressure declines, as indicated by the time-pressure curve in Figure 6. If the load were maintained further, the pressure would approach asymptotically its original value as indicated by the continuation of the first limb of the time-pressure curve. However, as the load is removed a second instantaneous adjustment takes place as a result of which the pressure drops to a minimum. The drop in pressure is theoretically equal to the initial increase in pressure. Following removal of the load the pressure recovers and tends towards its initial value, somewhat in accordance with the second limb of the time-pressure curve in Figure 6.

The time-deflection curve in Figure 6 shows the manner in which the aquifer is compressed by the load and subsequently expands following removal of the load. The rate at which compression or expansion proceeds at a point a given distance from the load is in general proportional, though not necessarily directly so, to the difference between the actual pressure at that point and the normal or initial pressure. Thus the rate of compression is initially maximal, as indicated by the slope of the time-deflection curve. As compression of the aquifer continues, the rate of compression becomes continually smaller. The first limb of the time-deflection curve approaches asymptotically the value of deflection determined by the magnitude of the load and by the elasticity of the solid material.

Initially the increase in load is shared by the confined water and by the solid material of the aquifer in accordance with their respective moduli of elasticity and depending on the porosity of the material. However, as the water flows radially away from the point of application of the load in response to the temporary gradient, a continually increasing proportion of the load is borne by the solid material. Ultimately, all of the increase in load is borne by the solid material of the aquifer, the hydrostatic pressure having been restored to its initial value.

Upon instantaneous removal of the load the aquifer expands, the initial rate of expansion being maximal. As the aquifer is assumed to be perfectly elastic, it ultimately returns to its original shape.

A comparison of the curve shown in Figure 5 with the theoretical time-pressure curve in Figure 6 indicates quite definitely that at least for the range of pressures involved the elasticity of the particular aquifer in question is reasonably perfect. Although not based on actual calculations, the theoretical curve is believed to be consistent with the assumptions made. And to the extent that these assumptions are met by the actual conditions the conclusion derived therefrom is believed to be sound.

In studying water-level fluctuations observed in artesian wells there frequently arise questions regarding the faithfulness with which the head in the well represents the pressure in the formation. And when such wells are equipped with automatic water-stage recorders there arise further questions with regard to the validity of the instrumental record as a reproduction of the fluctuations which occur in the well. These questions deserve consideration in connection with the record of Well S-201.

Obviously, unless a well is entirely shut off from the formation, under static conditions, at least, the head inside and outside the well should balance. And under such conditions an instrument should record the true position of the water-surface. However, the moment fluctuations in hydrostatic pressure occur in the aquifer the inertia and friction of the system and of the recording mechanism enter into the picture. Furthermore, there is to be considered the volume of water entering or leaving the well as the water-level rises or declines and consequently also the head required to move the water through the well-screen and radially through the formation toward or away from the well, as the case may be. It is merely a question of the relative magnitude of these effects and the particular fluctuation under observation.

The additional force required to overcome the frictional and inertial resistance of the recorder-mechanism causes the float to "lag" whenever there is a change in the water-level in the well. That is, if the stage is rising, the float is submerged more than usual, the increased displacement giving rise to the required additional force. On the other hand, if the stage is falling, the float is submerged less than usual. The difference between the position of the float relative to the water-surface at a given instant when the water-surface is in motion and its position relative to a static water-surface is spoken of as the "float-lag."

As there is reason to believe that, because of the nature of the bearings, the frictional moment is not wholly independent of the velocity of rotation of the drum as ordinarily assumed but is comparatively small for extremely low rational velocities, the lag during slow movements is doubtless negligible. Accordingly fluctuations occurring in artesian wells due to such causes as variations in atmospheric pressure and pumping from wells some distance away generally are faithfully reproduced by a recorder unless the bearings on the shaft of the drum are in rather poor condition. When the friction of the bearings is sufficient to cause an appreciable "float-lag," the same will be apparent, producing "steps" in the curve on the weekly recorder-chart. However, when rapid fluctuations in pressure occur, such as are produced by passing railroad-trains, the lag may be appreciable without leaving any such evidence of its presence. This is true with regard to records obtained using either of the special clocks as well as the usual weekly records.

It is evident that by changing the diameter of float-wheel on a given recorder the effect of the float-lag may be changed. For, given the diameter of the float and the vertical acceleration of the water-surface in the well, and assuming a constant frictional amount (independent of the angular velocity of the drum), the float-lag due to friction in the bearings on the shaft is inversely proportional to the diameter of the float-wheel. The float-lag due to inertia of the drum, shaft, and gears, neglecting the inertia of the float-wheel itself, is inversely proportional to the square of the diameter of the float-wheel. Thus any advantage gained by using a smaller float-wheel to increase the gage-height ratio is partly lost because of the accompanying increase in float-lag.

This was evident from a study of the curves for the nine west-bound trains on which detailed observations were made. When a small float-wheel was used, giving a gage-height ratio of 5.1 to 1, the trains produced an average fluctuation on the charts of only 0.019 foot. This is only about 63 per cent of the average fluctuation of 0.030 foot recorded on the weekly charts when the regular 1 to 1 gage-height ratio was used. However, in the case of the east-bound trains no such difference was found. The curves for the four east-bound trains obtained with the smaller float-wheel indicate that the magnitude of fluctuation on the charts produced by those trains averages 0.045 foot. This happens to be equal to the average fluctuation as recorded on the weekly charts.

The agreement obtained here is doubtless in part accidental owing to the paucity of the data. However, it is evident that with a given diameter of float-wheel the inertial lag is approximately proportional to the vertical acceleration of the water-surface in the well, whereas the frictional lag is supposedly independent of the angular acceleration of the drum and hence also of the vertical acceleration of the water-surface. Hence for small values of vertical acceleration the inertial lag may be quite small in comparison with the frictional lag regardless of the size of the float-wheel. However, for large values of vertical acceleration the inertial lag may be appreciable in comparison with the frictional lag, and, being inversely proportional to the square of the diameter of the float-wheel, is proportionately larger in the case of the smaller float-wheel, the frictional lag being inversely proportional to the first power of the diameter of the float-wheel.

It is seen, by comparing Figures 3 and 4, for example, that the maximum vertical acceleration, as indicated approximately by the curvature of the respective curves, is several times greater in the case of west-bound trains than in the case of east-bound trains, though the magnitude of the fluctuation is actually greater in the latter case. Moreover, it should be remembered that the curve shown in Figure 4 is probably a reasonable reproduction of the actual fluctuation because in that case the float-lag is small, whereas the curve in Figure 3 represents the actual fluctuation appreciably diminished because of lag. Hence a comparison of the actual fluctuations in the two cases would show a still greater difference in acceleration.

No attempt will be made at this writing to evaluate the stresses produced in the aquifer, except to state that such evaluation is theoretically possible. The problem of determining the distribution of stress produced in an isotropic semi-infinite body by a concentrated load acting normal to the surface was solved by Boussinesq [4]. By means of superposition this solution may be extended to non-uniform distributed loads. And, except as limited by the means at our disposal, it should be possible from the known distribution of stress within the aquifer to determine the accompanying increase in hydrostatic pressure and the variation of the same with distance from the applied load and with time as the water moves in response to unbalanced pressures. Actually the problem is beset with serious difficulties owing particularly to the successive discontinuities between the various strata. However, it appears that these difficulties may, in a measure at least, be overcome by resorting to certain simplifying assumptions.

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## DISCUSSION OF QUESTION NO. 2 OF THE INTERNATIONAL COMMISSION ON SUBTERRANEAN WATER: DEFINITIONS OF THE DIFFERENT KINDS OF SUBTERRANEAN WATER

O. E. Meinzer

The hydrologists who are concerned with the study of the water that occurs below the land-surface feel strongly the need of better agreement among the different countries as to the fundamental concepts of this branch of hydrology and as to technical terms to designate these concepts. For this reason, the question as to the definitions of different kinds of subterranean water was selected as one of the three questions for discussion by the International Commission on Subterranean Water at the meeting in Edinburgh in 1936 and again (as Question No. 2) at the meeting that is to be held in Washington in September, 1939.

The purpose of the International meetings is not only to discuss subjects of mutual interest but also, so far as practicable, to make official decisions. Obviously, decisions on scientific questions should be made only after mature consideration and only on questions as to which there is general agreement. The reports that have been prepared in different countries on the question under consideration and the correspondence and oral discussion appear to show that the way is open for International agreement on some of the basic concepts. A comprehensive paper on the question was prepared for the Edinburgh meeting by Dr. Vasilievskij, of Russia (Internat. Ass. Sci. Hyd., Bull. 22, 1936). Dr. Vasilievskij, in a letter dated January 12, 1939, urges that a beginning be made at the Washington Assembly to adopt new terms on the basis of Latin and Greek roots, these terms to have strict meanings for all countries. The following are tentative suggestions for such a beginning, based especially on information from France, Germany, Great Britain, Holland, Japan, Russia, and the United States.

Section 1--The water under discussion is that which occurs below the surface of the solid earth. It includes the water in liquid, solid, or gaseous state, but it does not include ice or snow that is on the surface (such as glaciers) or water that is in chemical combination. This water is designated as follows: Eaux souterraines (French); Suberrranean water and also underground water or subsurface water (English); Unterirdisches Wasser (German); Acqua sotteranei (Italian); Aguas subterraneas (Spanish).

It is believed that no new term is needed. Please add equivalent term in your own language.

Section 2--The branch of science which relates to subterranean water (Eaux souterraines) is called geohydrology. It is the field of the Commission on Subterranean Water (Commission des Eaux Souterraines).

Thus the branches of the science of hydrology that are covered by commissions in the International Association of Hydrology are as follows: Potamology--streams; limnology--lakes; cryology--ice and snow; geohydrology--subterranean water.

Section 3--Classification of subterranean water

(A) Water that occurs in the interstices of the rocks
  (1) In the zone of aeration
    (a) In the belt of soil-water
    (b) In the intermediate belt
    (c) In the capillary fringe
  (2) In the zone of saturation
    (a) Water that occurs in a permeable bed with no confining bed between it and the water-table and that has a pressure-head the same or nearly the same as the pressure-head of the water at the water-table
    (b) Water that occurs in a permeable bed overlain by a confining bed (either impermeable or with relatively low permeability) and that has a pressure-head sufficient to lift it (in a tightly cased well) to some level above the bottom of the confining bed
      (1) Water that is under sufficient pressure-head to rise (in a tightly cased well) above the land-surface (or above the surface of an overlying sea or lake)
      (2) Water that is under sufficient pressure-head to rise above the zone of saturation but not sufficient to rise above the land-surface
      (3) Water that is under sufficient pressure-head to rise above the bottom of the confining bed but not sufficient to rise above the zone of saturation
(B) Water that occurs in the interior of the Earth where interstices do not exist

[Note: It is recognized that the distinction between classifications (2-a) and (2-b) remains somewhat indefinite because it has not been found possible to give a precise definition of the term confining bed.]

Section 4--The water in Class (A) is designated Interstitial water; the water in Class (B) is designated Internal water.

Section 5--The Zone of Saturation is the zone in which the interstices are filled with water under hydrostatic pressure (except as they are filled with some other liquid, such as petroleum, or with entrapped gas). The hydrostatic pressure is commonly caused, directly or indirectly, by the force of gravity.

The Zone of Aeration is the zone in which the interstices are not filled with water under hydrostatic pressure (except temporarily) but may be filled or partly filled with water that is held against the pull of gravity by the force of molecular attraction. If an impermeable body of rock lies in a position between the two zones, it is considered to be in the zone of aeration.

In some places there are two or even more zones of saturation with intervening zones of aeration.

Section 6--The Water-table is the upper surface of the zone of saturation except where that surface is formed by an impermeable body. Where it is formed by an impermeable body there is no water-table.

The French term Niveau d'eau and the German term Grundwasseroberfläche denote the same concept as the English term Water-table, and etymologically these terms are closely equivalent. No new term is proposed.

If a well is sunk into a permeable material just to the point where water enters the well and forms a water-surface in it, that surface marks the hydrostatic level of the water at the top of the zone of saturation; by definition, it indicates the position of the water-table at that place. Wherever there is a body of permeable material that is saturated with water in its lower part, there is a zone of saturation and a water-table. The water-table is not a water-surface such as the water-surface in the well. (Er ist nur im Brunnen wirklich ein Spiegel.) The corresponding water-surface in the permeable material (held up somewhat by the force of molecular attraction) is in general above the water-table and is very irregular and interrupted, consisting of many little surfaces that are concave upward, each occupying an interstitial chamber that may be connected with its neighbor by a tiny strait or walled off from it by a grain of sand.

Section 7--New International terms are needed to designate the water in the zones of aeration and saturation. The following terms are proposed:

(1) Kremastic water (water in the zone of aeration)
(2) Plerotic water (water in the zone of saturation)

The term kremastic is derived from a Greek word denoting suspension, and the term plerotic from a Greek word denoting saturation.

[Note: It is not expected that these terms will entirely replace satisfactory terms that are well established in the different languages, such as suspended water (water in the zone of aeration), or ground-water and Grund Wasser (water in the zone of saturation).

Section 8--The belt of soil-water (also called the root-zone) is that part of the solid earth, directly below the land-surface, from which water is discharged into the atmosphere in perceptible quantities by the action of plants or by evaporation from the soil [(1-a) in Section 3].

The capillary fringe is the belt that overlies the zone of saturation and contains capillary interstices some or all of which are filled with water that is continuous with the water in the zone of saturation but is held above that zone by capillarity acting against gravity [(1-c) in Section 3].

The intermediate belt is that part of the zone of aeration which lies between the belt of soil-water and the capillary fringe [(1-b) in Section 3].

[Note: The concepts in this section are proposed for International agreement but not the terms belt of soil-water, capillary fringe, and intermediate belt.]

Section 9--The following International terms are proposed to designate different kinds of water in the zone of aeration:

Kremastic water
   (a) Rhizic water [(1-a) in Section 3]
   (b) Argic water [(1-b) in Section 3]
   (c) Anastatic water [1-c) in Section 3]

The term rhizic is derived from the Greek word denoting roots of plants, the term argic from the Greek word "inactive," and the term anastatic from the Greek word denoting the act of standing up.

Section 10--The following International terms are proposed to designate different kinds of water in the zone of saturation:

Plerotic water
   (a) Phreatic water [(2-a) in Section 3]
   (b) Piestic water [(2-b) in Section 3]
      (1) Hyperpiestic water
      (2) Mesopiestic water
      (3) Hypopiestic water

[Note: The term phreatic water is derived from a Greek word denoting a well. It was used in French by A. Daubrée (Les Eaux souterraines a l'Epoque actuelle, v. 1, p. 19, Paris, 1887), who included under this term only the water in the upper part of the zone of saturation [essentially (2-a) in Section 3]. Water-Supply Paper 494 (Outline of ground-water hydrology, with definitions, by O. E. Meinzer, pp. 5, 22, 23, 1923) followed R. A. Daly (Genetic classification of underground volatile agents, Econ. Geology, v. 12, pp. 495, 499, 1917) in using it to designate all water in the zone of saturation. It is understood, however, that in French the term is still used as defined by Daubrée.]

No satisfactory terms have been available in English to denote the waters classed as (2-a) and (2-b). For (2-a) such terms as "free water," "unconfined water," and "nonartesian water" have been used. For (2-b) the term "artesian water" has been used but that term is also used in various more restricted senses, such as water that has sufficient pressure-head to rise above the land-surface [classification (2-b-1)].

The term piestic is derived from a Greek word denoting pressure.

Acknowledgment--In developing the terms of Greek origin I have had the help of different Greek students, but am especially indebted to R. C. Cady of the Geological Survey.

U. S. Geological Survey,
   Washington, D. C.,
      April 21, 1939

## ARTIFICIAL DRAINAGE OF LAND: STREAM-LINE EXPERIMENTS
## THE ARTESIAN BASIN--I

Don Kirkham

In July, 1928 [see 1 of "References" at end of paper], Gardner, Israelsen, and McLaughlin pointed out that for the case of steady flow of water through homogeneous soil, the permeability-constant cancels out of the Laplace equation for the potential function derived from the basic theory. Subsequently Gardner and Farr [2] computed the maximum distance allowable between tile-drains, installed for intercepting the upward flow of water from an artesian basin, and published their conclusions in the December, 1933, number of Agricultural Engineering. This distance depended upon the depth and diameter of the drains, the depth of the confining overburden of soil, and the pressure in the water-bearing stratum, but not on the permeability-constant.

Figure 1 is photographed from the Gardner-Farr paper. This exhibits the stream-line pattern expected from the theory. Although in their figure the soil is shown uniform throughout, it is to be inferred that this pattern would not be changed if the soil on one side of the vertical plane midway between drains were fine and on the other side coarse.

In order to make an experimental check, a small sand tank model, 29 by 19-1/2 by 2-1/2 inches in size with a plate-glass front, was constructed. In the bottom, resting on a perforated brass plate in contact with water, was a layer of coarse pebbles and above that was introduced fine sand on one side and coarse on the other. This was put in with care, separated by a temporary movable partition that could be raised and finally removed, leaving the two sands in contact over a vertical plane interface.

Provision was made for the introduction of coloring matter at a series of inlets along a horizontal line near the bottom and next to the glass. Drains were placed a few inches below the surface at the sides of the tank as was shown in Figure 1, and a constant hydrostatic pressure was maintained in the pebble-layer. The boundary-conditions were thereby definitely fixed, the line of separation between the two sands, according to theory, forming a stream-line.

It was to be expected that the amount of flow through the coarse sand would exceed that through the fine, but that the stream-line patterns would be symmetrical with respect to the vertical plane separating the sands. Figure 2 shows the results of the test and confirms the theory. The mean diameter of the fine sand-particles was approximately half that of the coarse and the water that passed through the fine was approximately one-fourth that passing through the coarse.

Another test was made with a drain at the center opened and the two side-drains closed. Figure 3 shows the results of this test and here again there is symmetry.

Additional tests were made with varying boundary-conditions, the soil being uniform throughout and the technique improved. The procedure then followed was to establish a state of steady flow with the drains closed. The coloring matter was permitted to enter and move continuously in the direction of general flow, producing finally a pattern of vertical stream-lines one for each inlet, as shown in Figure 4. The drains at the side and in the center of the model were then opened and it was presumed that the existing pressure-field would be modified quickly to conform to the new boundary-conditions, whereas the coloring matter would begin moving slowly along an infinite set of new stream-lines, which in general would intersect the lines of the old pattern at finite angles, and finally stabilize in a pattern coinciding with the actual stream-lines determined by these new boundary conditions.

Figures 5, 6, and 7 are photographs taken at arbitrary times as the patterns developed interesting features. From the nature of the patterns shown on these photographs taken during this transitory stage, interesting information may be inferred concerning the velecity-distribution throughout the region.

Figure 8 shows the final steady state of flow. On this photograph of the model, dimensions corresponding to those of an actual field case are given. The gravel-layer is 50 feet below the surface of the ground; drainage-pipes nine inches in diameter are buried at a depth of nine feet,

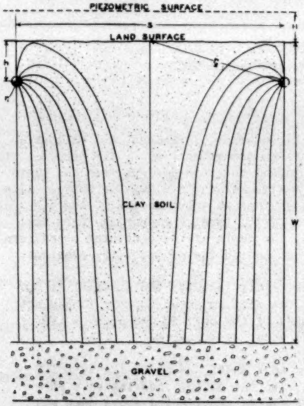


*FIG. 1—EXPECTED FLOW-PATTERN FOR CASE OF FLOW INTO DRAINS FROM AN ARTESIAN BASIN (GARDNER AND FARR)*

Figs. 2 and 3--Stream-line flow into drains, coarse sand on right, fine on left; flow-pattern and hence pressure-distribution is independent of permeability

Fig. 4--Vertical stream-line flow in undrained land overlying an artesian basin

Fig. 5, 6, and 7--Artificial drains operating to intercept vertical flow from artesian basin; show manner in which water originally in vertical "lines" of Figure 4 is carried to drains; pictures were taken at arbitrary time-intervals after drains had been opened; "lines" of Figure 4 are stream-lines but colored patterns of Figures 5, 6, and 7 are not; the actual stream-line pattern is shown in Figure 8

Fig. 8--Stream-line flow into drains; two complete drain-sections shown for drain-spacing 41 feet and pressure-head eight feet above soil-surface

Fig. 9--Stream-line flow into a drain; one complete drain-section shown for drain-spacing 82 feet and pressure-head four feet above soil-surface

Fig. 10--Inadequately drained land; one-half drain-section is shown for drain-spacing 164 feet and pressure-head two feet above soil-surface (note that two-thirds of surface is covered with water)

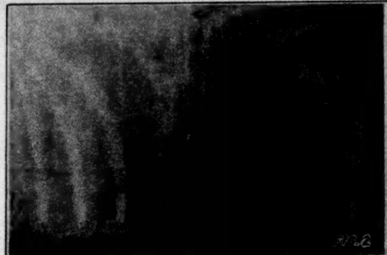
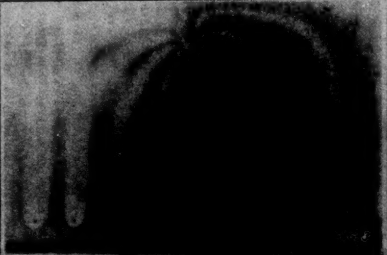


FIG. 2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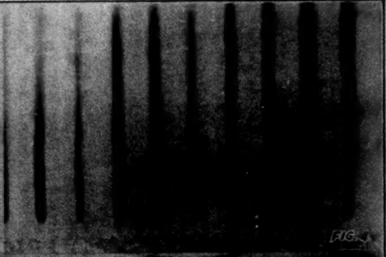
FIG. [illegible]

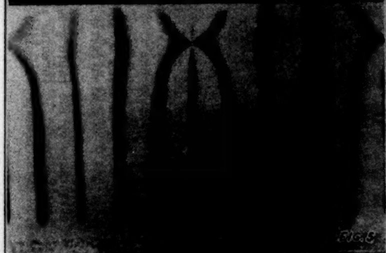
FIG. 5

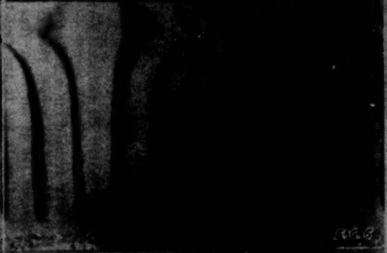
FIG. 6

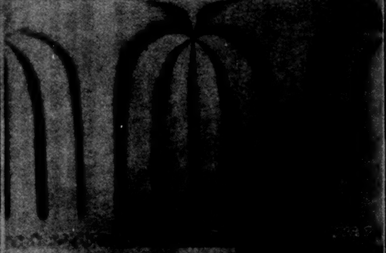
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FIG. [illegible]

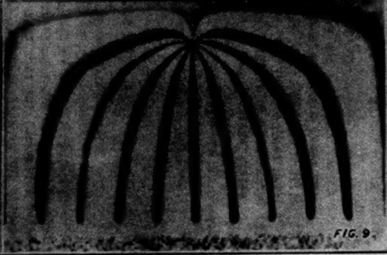
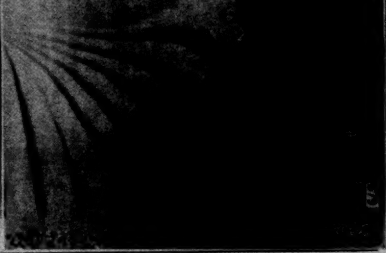


FIG. 9.



and spaced 41 feet apart. The pressure in the gravel-stratum is such that the water in a static well bored into the gravel would rise to a height of eight feet above ground-level.

As implied above, the drain-spacing could be varied by opening or closing certain drains. In Figure 9 the spacing was doubled and the pressure-head above the land-surface reduced to half. The flow-pattern shows that all the underground-water enters the drain--none penetrating the surface. Note, in particular, that the marginal stream-lines enter the drain.

Figure 10 shows one-half of a drainage-section, corresponding to a drain-spacing of 164 feet and a head above the land-surface of two feet. This again doubles the spacing and reduces the pressure-head to one-fourth of the original eight feet, but the drainage is obviously decidedly inadequate. Water covers more than two-thirds of the soil-surface. This water-layer appears as a black line in the photograph. More than one-fourth of the vertical flow must follow a path over the surface of the ground in order to reach the drain.

In the paper which has been presented the tests shown agree in a qualitative way with the analytical theory. Further studies are under way in which the theory will be applied to various boundary-conditions for the purpose of obtaining quantitative comparison of theory with experiment.

The author wishes to acknowledge with kind appreciation the generous aid and useful suggestions given during the course of these experiments by Dr. Willard Gardner and Dr. Leon B. Linford.

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# THE ROLE OF EVAPORATION IN THE HYDROLOGIC CYCLE

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Hydrologists have recognized a serious need for means of measuring water-losses resulting from evaporation and transpiration from drainage-areas, from land-surfaces as well as from free-water surfaces. The fact that only a portion of the water from a given rainstorm can be accounted for as surface-runoff and base-flow is due to the fact that a part is required to replace the field-moisture which has been removed from the soil by evaporation and transpiration since the previous rain.

In the unit-graph method of computing hydrographs from precipitation-data the principal difficulty is due to uncertainty as to the magnitude of the runoff-coefficient. In the channel-storage method the chief difficulty is related to lack of knowledge as to the rate at which field moisture-deficiency develops. In both cases, if data on losses from the watershed by evaporation and transpiration were available, they could be subtracted from the precipitation-values and remainders obtained which would permit the determination of the actual amount of water available for runoff.

It is recognized that evaporation-pans and atmometers do not supply actual information on water-losses from drainage-areas or even from lakes and reservoirs. Many attempts have been made to derive from such evaporation-data empirical formulas which will give, in terms of meteorological data, an accurate measure of evaporation-losses from lakes and evaporation and transpiration-losses from land-surfaces. Most of these formulas are variants of Dalton's original statement and contain the expression $W(e_w - e_a)$, in which $e_w$ and $e_a$ are vapor-pressures of the water-surface and the air, respectively, and $W$ is a wind-factor.

Recent studies in aerodynamics stimulated by the rapid growth of aviation have produced results which indicate that these empirical evaporation formulas cannot be defended on physical grounds. These studies in aerodynamics have, however, supplied knowledge of atmospheric turbulence and the mechanism of turbulent interchange which has made possible the development of a method for determining the evaporation not only from free water-surfaces but from land-surfaces as well [see 1 of "References" at end of paper].

In the lower atmosphere there are two distinctive layers known as the boundary or laminar layer and the turbulent layer. In the former or laminar layer, which is adjacent to the ground, the transport of water-vapor proceeds by way of simple diffusion. In the turbulent layer the transport takes place by mechanical mixing which tends to establish an adiabatic distribution of properties of the air. Thus, for water-vapor in the turbulent layer differences in moisture-concentration tend to become eliminated. If, however, water-vapor is continually being added to the turbulent layer from below by evaporation, a moisture-gradient will necessarily be established with the vapor-concentration highest at the base and diminishing upwards. When the ground is dry and there is no supply of moisture available for evaporation, the vapor-addition from below ceases and the moisture-concentration throughout the turbulent layer becomes uniform.

On the other hand, if water-vapor is abstracted from the base of the turbulent layer by condensation or absorption, a vapor-gradient directed downward will be established. Here again, when the abstraction of moisture ceases, the vapor-gradient is destroyed by the turbulent mixing which immediately establishes a uniformity of moisture-concentration. With a given intensity of mixing in the turbulent layer, the rate of evaporation will be directly proportional to the moisture-gradient that will be maintained. Conversely, in order for a given moisture-gradient to persist, the greater the intensity of turbulent mixing the greater will be the required evaporation.

It should be emphasized that the laws of transfer for the boundary and turbulent layers are distinct and independent of each other. Measurements of physical variables within these two layers cannot therefore be applied indiscriminately to either layer, without regard for the nature of the laws of transfer. Because of instrumental limitations it is virtually impossible to deal with the boundary-layer directly, whereas physical measurements in the turbulent layer are easily obtained.

Thus, it is possible to determine evaporation and transpiration from and condensation to any surface by observing the vapor-pressure gradient between two levels in the turbulent layer and the intensity of turbulent mixing along this gradient. The general form of an equation for evaporation based on these facts is

$$E = -A(dq/dh)$$

in which A is the "Austausch" coefficient, or the coefficient of turbulent mixing; and (dq/dh) is the rate of change of moisture-concentration with respect to height above the evaporating surface. When developed for an installation where the upper observations are taken 25 feet and the lower ones 4.75 feet above the ground the theoretical expression, giving evaporation in inches per hour, becomes

$$E = 0.0703\ P(q_1 - q_2)(u_2 - u_1)/(T + 459.4)$$

where P is pressure in inches of mercury, $q_1$ and $q_2$ are specific humidity in grams of water per kilogram of air at the lower and higher levels, respectively, $u_1$ and $u_2$ are wind-velocities in miles per hour at the lower and upper levels, respectively, and T is temperature in °F.

It should be clear that this expression does not involve correlation between observed evaporation from pans of various size, shape, and exposure, or of various meteorological elements and the true moisture-losses from watersheds and lakes, but measures directly the actual emission of water-vapor from an evaporating surface. Thus, in order to determine the loss of water by evaporation from a reservoir it is only necessary to install an instrument over the reservoir-surface and measure it; just as to determine the loss from the reservoir by surface-outflow one would measure it by means of a wier or flume at the outlet. Surface-discharge in a stream is the product of cross-sectional area and current-velocity. In the same way, water-vapor discharge into the air is the product of cross-sectional area, which may be taken as unity, and velocity of vapor-transport aloft which is expressed in terms of the intensity of turbulent mixing and the gradient of moisture-concentration. Consequently, this technique supplies a means of measuring the upward movement of water comparable to present methods of measuring flow in channels.

The virtue of this technique is that it permits the determination of flow of moisture in either direction as evaporation or condensation and can be used for measuring moisture-loss from any surface; for a field or a watershed as well as a free-water surface.

*FIG. 1—EVAPORATION INSTRUMENTAL INSTALLATION AT ARLINGTON FARM, VIRGINIA*

An evaporation-station was established over a meadow at the Arlington Experimental Farm on October 1938 (Fig. 1) since when it has been operated continuously except for some unavoidable interruptions. Figure 2 shows the march of moisture-concentration at the two levels for two days in early autumn during which time a modified Polar Continental air-mass remained over the area. The sky was clear and moderate temperatures prevailed. The air-mass was relatively stagnant with light and variable winds. Significant radiational cooling occurred throughout the night and a moderate ground-fog was observed.

During the first night the moisture-concentration of the air dropped to a minimum of 5.4 and 5.8 grams in the lower and upper levels due to abstraction of moisture by condensation at the ground. As soon as the ground began to warm up after sunrise and evaporation commenced, moisture-concentration rose rapidly, beginning at the lower level and producing a reversal in the gradient. Shortly before noon thermal convection had developed to a point where the moisture was carried to the upper air faster than it was

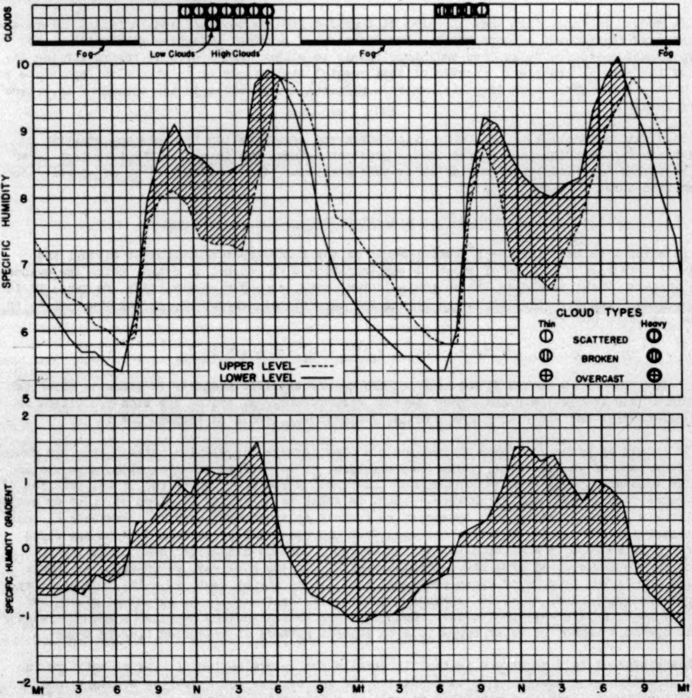

*FIG. 2—MARCH OF MOISTURE-CONCENTRATION AT TWO LEVELS AND OF MOISTURE-GRADIENT, OCTOBER 15 AND 16, 1938, ARLINGTON FARM, VIRGINIA*

received from the ground and the concentration at both levels diminished about 0.8 gram. In late afternoon, with a diminution of convection, the evaporation again exceeded the rate of transport aloft and the moisture-concentration rose to the high point of the day. Between 6 and 7 p.m. the cooling of the ground-surface began, and soon the concentration at both levels was the same. With continued cooling condensation was initiated, and as moisture was abstracted from the lower level the gradient was reversed, and the concentration at both levels diminished throughout the night. In the morning there was a heavy dew-deposit.

The same sequence of conditions was repeated the next day; first, an upward shift of gradient followed by a rapid increase of moisture-concentration as evaporation proceeded; then a diminution of concentration with a continued upward-directed gradient as thermal convection carried the moisture to the drier levels aloft; then, as convection subsided, a rapid increase in concentration; and finally, with the onset of ground-radiation at the end of the day, condensation, a gradient directed downward, and a rapid diminution of moisture.

This sample-record shows that the moisture-concentration at the two observation-levels within 30 feet of the ground varies so much that the variation can readily be measured. During mid-afternoon the specific humidity at the lower level exceeded that at the upper as much as 1.6 grams whereas at midnight the air at the lower level was drier than that at the upper by 1.2 grams. At this time the wind instruments had not yet been installed so it was not possible to determine

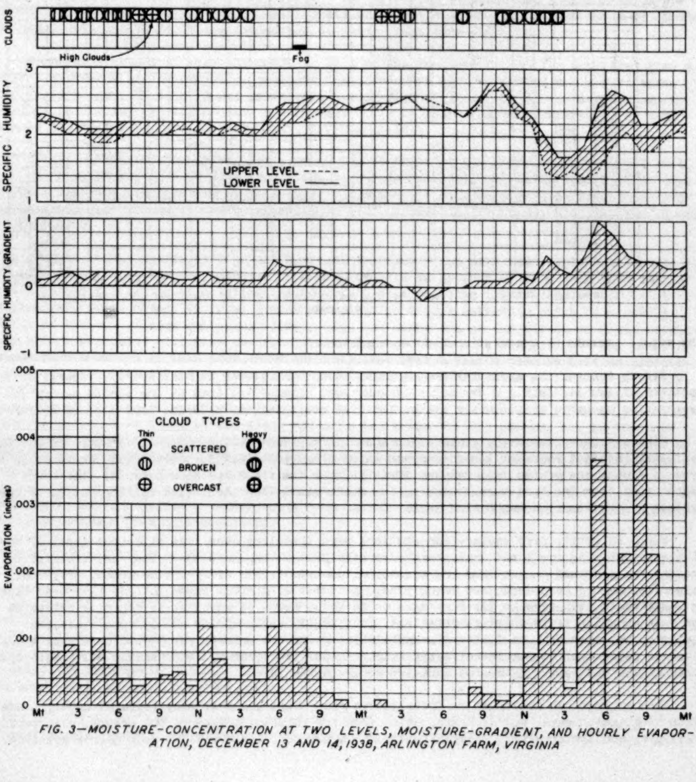

*FIG. 3—MOISTURE-CONCENTRATION AT TWO LEVELS, MOISTURE-GRADIENT, AND HOURLY EVAPORATION, DECEMBER 13 AND 14, 1938, ARLINGTON FARM, VIRGINIA*

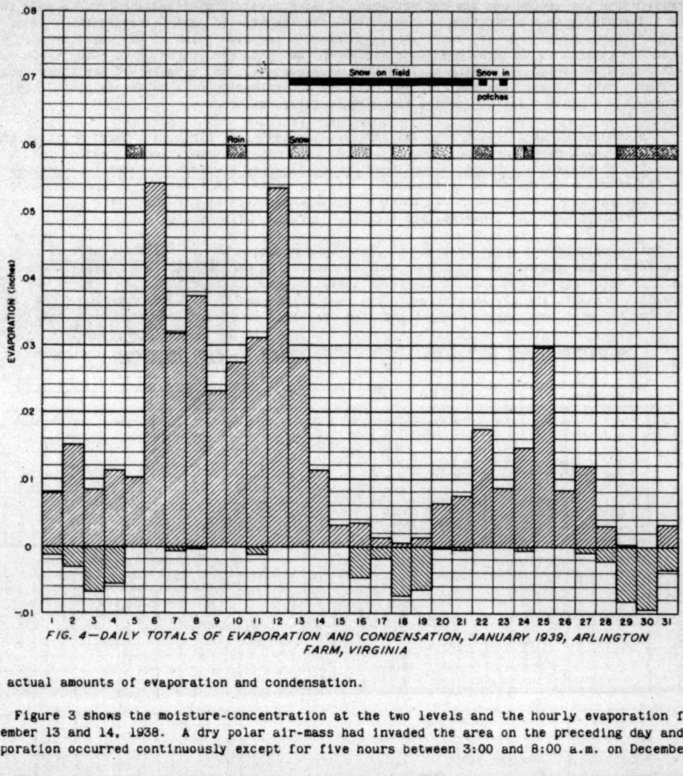

*FIG. 4—DAILY TOTALS OF EVAPORATION AND CONDENSATION, JANUARY 1939, ARLINGTON FARM, VIRGINIA*

the actual amounts of evaporation and condensation.

Figure 3 shows the moisture-concentration at the two levels and the hourly evaporation for December 13 and 14, 1938. A dry polar air-mass had invaded the area on the preceding day and evaporation occurred continuously except for five hours between 3:00 and 8:00 a.m. on December 14.

Figure 4 shows the daily evaporation and condensation for the month of January, 1939. The most striking fact revealed was the way in which evaporation was suppressed and condensation increased during the period from January 13 to 21 when the field was snow-covered. The total evaporation from the land-surface during the month was 0.4747 inch. The moisture added to the surface by condensation was 0.0632 inch.

Early in April, five evaporation-stations were installed over five different types of cover at the National Agricultural Research Center near Beltsville, Maryland. They are designed to measure the combined evaporation and transpiration from fields of rye, blue-grass, perennial lespedeza, annual lespedeza, and young pine. A number of similar installations have been made in a watershed tributary to the Muskingum in Ohio, by means of which it is hoped to determine the rate at which field-moisture deficiency is actually built up for use in runoff-studies. Equipment has been sent to California and a station for the primary purpose of obtaining a quantitative measure of the amount of water which the soil receives by condensation will begin operation on the University Campus at Berkeley early in May [2].

When evaporation-stations are installed in many areas and over many types of cover, a new class of climatic data, namely, evaporation from the natural surface of the ground, will become available, and the problems associated with the hydrologic cycle will be much nearer solution.

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## DISCUSSION

WALDO E. SMITH (Hydraulic Engineer, Muskingum Watershed Conservancy District, New Philadelphia, Ohio)--It appears that the conception and development of the evapo-transpiration meter described by the authors is monumental in the field of hydrologic and meteorologic instrumental development, comparable in recent times to the development of instruments for upper-air observation. For the first time it makes possible the determination of the water-use of a field of growing crops or the evaporation-loss from a fallow field. By means of observations over various areas over successive years, it should be possible to establish the water-requirements of growing crops in specific soils and climatic provinces. Day by day as well as full season uses may be determined. Heretofore experiments on small plots under quite artificial conditions have provided the chief data available in the evaluation of water-requirements.

Inasmuch as movement of vapor downward as well as upward is recorded, for the first time a concrete measurement of the amount of moisture that condenses in the form of dew can be made. In many regions possibly this is not important, but in regions receiving a considerable amount of moisture during the growing season in this way, it is of almost as much importance to agriculture as the measurement of the water that falls as rain.

We likewise have for the first time a means for determining the actual evaporation from a body of water which may vary in size from a few acres upward. This is vastly important to engineers concerned with the problems of water-supply and the losses by evaporation from reservoirs and it is urged that the equipment be established over representative reservoirs over the country at an early date.

As usual with the development of an important instrument, as many new problems are posed as old problems solved. Among the unsolved problems involved in the use of data from this instrument will be the difficulty of relating the plot-data obtained (the information is for relatively homogeneous, small areas) to total evapo-transpiration from a watershed which is a complex composite of plots. It does not appear likely that the summation of the effect on plots weighted for the entire watershed will give correct results for a watershed as a whole. We may possibly be guided to a solution of this problem by the fact that over a year's time we have an approximate value of the total losses by evaporation and transpiration providing we have satisfactory measurements of precipitation on the watershed and of stream-flow at the outlet of the watershed. The fundamental hydrologic equation for long periods of time is $P = (R + L)$, in which $P$ is average precipitation, $R$ is total stream-flow, and $L$ is the value for the losses, all in the same units, usually inches of depth on the watershed. The losses usually are almost entirely due to evaporation and transpiration. For shorter periods of time and for a year as well if storage at the beginning and end is much different, this equation must be corrected for the increment, either negative or positive, to the water in storage in the ground or in reservoirs. It will be interesting to see the degree to which these data in the composite will check the close approximation as determined from this equation.

One of the difficulties which causes the writer to believe that the sum of weighted values for plots is not equal to the whole are the conditions induced at the boundaries between types of surface-conditions. The instrument is set far enough from the boundary to overcome this effect, and thus in weighting the values secured for the plots, the condition would not be taken into account. Should we have an extended area of bare, fallow land adjacent to a wheat field it is quite possible that the evaporation on the border of the wheat field next to the fallow land, assuming that it is the windward edge of the wheat field, will often be much larger than will occur where the instrument is set. A more likely instance of this sort is a lake or reservoir in the heart of an arid or semiarid region.

The authors do not discuss the matter of the size of the field in the middle of which the instrument should be set. Possibly under ordinary conditions where the change from field to field is not great a 40- or 60-acre field may suffice, but where the changes are great the area will probably need to be much greater. How far the instrument should be set from the windward edge of a lake in an arid region to obtain stable conditions free from the boundary-effect will probably need to be established by trial.

The authors mention that during the period of snow-cover in the case of data cited, the evaporation was low and condensation was relatively great. It is doubtful if this condition is typical of the area over which there is snow-cover for several months of the winter. Apparently in the instance cited the surface-temperature of the snow was lower than the temperature of the air. This is not characteristic of the area on which snow-cover remains for several months of the year. To those who live within that region it is observable that much evaporation occurs directly from the ice- and snow-surfaces. It is not uncommon for people to hang freshly washed clothes on the line for a day or two to let them "freeze dry."

The success of the instrument in the proper measurement of vapor-movement, either upward or downward, depends upon the existence of turbulent flow of air. The occurrence of laminar flow is not discussed but is probably more frequent at interior locations in the winter and at night than at times that convective currents are induced. It would appear that the data collected should be used with caution to avoid misinterpretation. Especially in hilly country where air-drainage is considerable does this caution seem especially important to the writer.

It is further to be urged that an attempt be made to correlate measurements from the Class A Weather Bureau evaporation-pan, the Colorado land-pan, the atmometer, and other devices now in use to measure evaporation with the results obtained by means of the new instrument. This should probably be done by locations without reference to plots. Most evaporation-pans evaluate chiefly the potentialities of the atmosphere to pick up moisture at a given location, moisture for evaporation being always available. The new device measures the actual evapo-transpiration, which at times depends upon the potentialities of the atmosphere to pick up moisture, at other times depends upon the availability of moisture. In general, potentialities go down as general availability increases, and it would thus appear that the evapo-transpiration might turn out to be a function of precipitation and an inverse function of evaporation from a Class A pan.

In southeastern Ohio on the basin of the Walhonding River, the 15-year annual average rainfall is about 39 inches and the runoff is 13.3 inches, leaving for losses by evapo-transpiration about 25.7 inches. The pan-evaporation at Wooster, near the watershed toward the east, making reasonable allowance for the five colder months during which the pan is not in operation, is a little more than 33 inches. Over the 15-year period the evapo-transpiration was about 77 per cent of the observed pan-evaporation. No attempt has been made to establish this value year by year though this is possible with present data. The new instrument should ultimately make possible the evaluation of this ratio month by month and possibly even day by day, thereby greatly increasing the usefulness of the pan-evaporation data accumulated over past years.

## SOIL MOISTURE-CONTENT UNDER VARIOUS CONSERVATION PRACTICES

O. R. Neal

(Contribution from the Soil Conservation Experiment Station, U. S. Department of Agriculture, Clarinda, Iowa, in cooperation with the Iowa Agricultural Experiment Station, Ames, Iowa)

Notwithstanding the considerable amount of investigational work on soil- and water-conservation that has been performed and reported during recent years, little attention has been given to the effects of treatments and practices on soil moisture-content. During most years in the Missouri Valley Region, and particularly during the past three years of deficient precipitation, the conservation of water has been of paramount importance in the production of crops. In many cases the amount of available water in the soil has been the limiting factor in crop-growth and productivity.

In the course of our investigations concerning methods of soil- and water-conservation, soil moisture-content under certain conditions and treatments has been studied rather intensively. It is intended herein to present certain averages and summaries from these data. Conditions of moisture observed on these areas should be indicative of the effect to be expected from certain conservation-practices in the Missouri Valley soil-area. The discussion will be limited to results obtained during the period 1936-1938.

The normal rainfall is calculated from a series of nearby Weather Bureau stations, the record

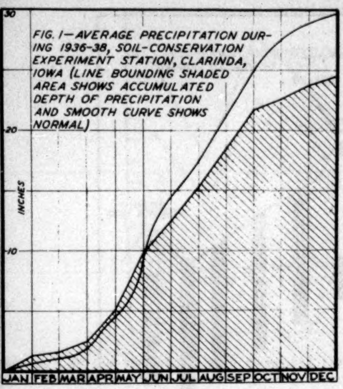

FIG. 1—AVERAGE PRECIPITATION DURING 1936-38, SOIL-CONSERVATION EXPERIMENT STATION, CLARINDA, IOWA (LINE BOUNDING SHADED AREA SHOWS ACCUMULATED DEPTH OF PRECIPITATION AND SMOOTH CURVE SHOWS NORMAL)

from each being weighted in inverse proportion to the distance from the Soil Conservation Experiment Station. The five Weather Bureau records used vary in length from 10 to 63 years. Precipitation during the period of this study has been below the calculated normal each year, the accumulated deficiency amounting to slightly less than 16 surface-inches or approximately 18 per cent. Figure 1 shows the average precipitation accumulated by months, and the departure from normal for the three-year period. It is evident that the period was one in which moisture-conservation was extremely important in connection with crop-production.

The Marshall silt-loam is characterized by a fairly rapid rate of infiltration. Baver [see 1 of "References" at end of paper] states that the rate and amount of infiltration of water by force of gravity is largely dependent on the non-capillary porosity of the various layers in the soil-profile. He points out that the non-capillary pore-space of the Marshall soil amounts to approximately 25 per cent of the total volume of soil throughout the three-foot profile. This condition should permit a uniform and reasonably rapid rate of entry and movement of water in the surface-layers. It would be expected that amounts of water entering the soil at the time of a storm would be rather readily distributed until the moisture-content of the wetted portion was reduced to field-capacity. This rapid distribution of moisture has been repeatedly observed under field-conditions.

Samples for moisture-determination were taken in the profile at depths of 0 to 6 inches, 6 to 12 inches, 1 to 2 feet, and 2 to 3 feet in all cases. In the terrace cross-section study, depths of sampling were extended to six and seven feet as shown. The soil taken from each depth-interval was mixed and a sample was taken for moisture-determination. Moisture is measured in percentage on an oven-dry basis.

In the comparison of terraced and unterraced areas, each datum represents a weighted average of 60 moisture-determinations during the three-year period. Losses of water as surface-runoff have been very small, amounting to approximately two per cent of the total precipitation on the unterraced areas and less than one per cent on the terraced area. In the case of the terrace cross-section study, each datum represents the average of 27 moisture-determinations. No runoff occurred from these terraces during the period of study. In the comparison of the contoured area with the area having rows in the direction of slope, each datum represents the weighted average of 36 determinations. Runoff from the contoured area amounted to two per cent of the total precipitation, while that from the non-contoured area was six per cent.

Since the soil moisture-content under various parts of the terrace-system varies widely and

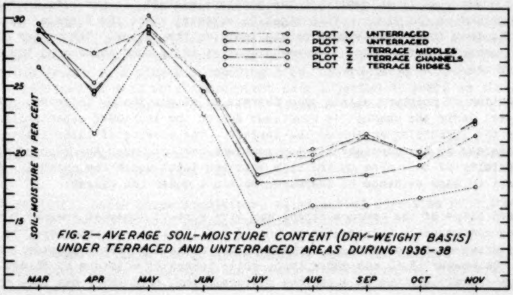

FIG. 2—AVERAGE SOIL-MOISTURE CONTENT (DRY-WEIGHT BASIS) UNDER TERRACED AND UNTERRACED AREAS DURING 1936-38

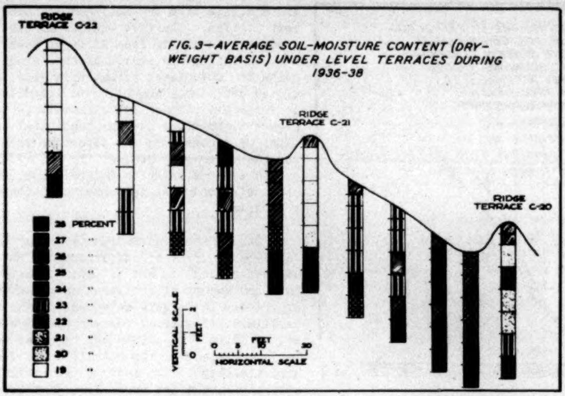

FIG. 3—AVERAGE SOIL-MOISTURE CONTENT (DRY-WEIGHT BASIS) UNDER LEVEL TERRACES DURING 1936-38

consistently, under the conditions studied, these data have been presented separately for ridges, middles, and channels. It is hoped that this procedure will convey a more accurate picture of actual conditions than would be obtained from an average of these rather widely divergent values.

The data in Figure 2 show the average moisture-content by months under the three divisions of a terraced area and two unterraced areas. Plot V represents an unterraced area with a northeast slope, plot Y is unterraced with a southeast slope, and plot Z is terraced with a northeast slope. The degree of slope and cropping plan is the same on each of the areas. Plots V and Y thus provide opportunity for a study of the influence of direction of slope, while plots V and Z permit a comparison between a terraced and unterraced area, where all other factors are constant.

In the case of the unterraced areas there is no evidence of a consistent difference in soil moisture-content as a result of direction of exposure. This has been apparent throughout the rather wide fluctuations in moisture-level which have occurred during each season.

A comparison of the terraced and unterraced areas indicates that the moisture-content under the terrace-channels has been slightly higher than that for the unterraced area. The terrace middles have been somewhat below the untreated area, while the terrace ridges have shown a moisture-content considerably lower than that for any of the other sampling locations.

The data in Figure 3 show the results of a more intensive study of moisture-conditions under two level terraces. Samples were taken to a depth of six feet in the channels and middles and to a depth of seven feet under the ridges. The average moisture-content of the various layers at each location is shown. It is evident that the moisture-content, in general, increases at successively lower points on the slope. This might be expected since the loessial mantle normally decreases in depth from the ridge-tops to points lower on the slopes. The rather impervious glacial material underlying the loess is somewhat nearer the ground-surface at the lower terrace than at the upper one.

The distribution of moisture within each terrace is of particular interest. The relatively high moisture-level under the channel is doubtless due to the increased opportunity for infiltration afforded by the impounding action of the terrace. The absence of lateral movement of soil-moisture is emphasized by the consistently low moisture-content under the terrace ridge, notwithstanding the proximity of this area to the high moisture-level under the channel. Below depths of five feet there is some evidence of increased moisture under the ridges.

The increased slope of the terrace ridges may give rise to somewhat greater runoff from the ridge-surface and consequently a decreased amount of infiltration. Furthermore, it appears possible that the increased area of surface exposed on the ridge may permit greater losses of water by evaporation. Veihmeyer [5,6] has shown that, while losses of moisture by direct evaporation from the soil are largely limited to a shallow surface-layer, this layer may lose moisture very

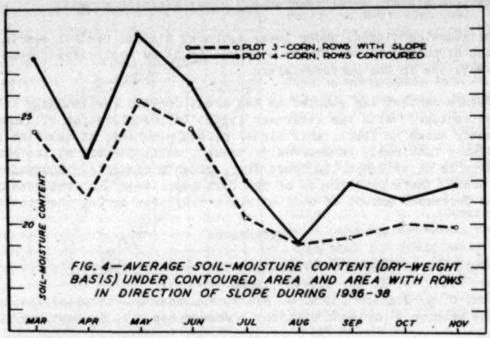

FIG. 4—AVERAGE SOIL-MOISTURE CONTENT (DRY-WEIGHT BASIS) UNDER CONTOURED AREA AND AREA WITH ROWS IN DIRECTION OF SLOPE DURING 1936-38

rapidly. It has previously been shown [4] that in the Marshall silt-loam a large percentage of the water absorbed from storms of average duration and intensity may be held in the surface eight inches. This moisture would thus be subject to more or less rapid evaporation. If the wetting and drying processes were repeated frequently, the total loss of soil-moisture by evaporation during the year might be quite large. That this is the case has been shown [3] for a fallow Marshall soil. The average moisture-loss by evaporation over a period of four years has amounted to approximately 55 per cent of the annual precipitation. Under a growing crop, evaporation from the soil-surface would doubtless be markedly reduced.

The influence of contouring on soil moisture-content has also been studied. Two adjoining areas having the same length and degree of slope have been cropped to corn continuously during the period of investigation. Operations of plowing, planting, and cultivation have been performed at the same time on each area. Corn is planted with a loose-ground lister. In one case the rows run in the direction of slope, while on the other area the rows are on the contour. The average moisture-content, by months, for each of the areas during the three-year period from 1936 to 1938 is shown in Figure 4.

The data show that during the period from March to July the moisture-content was appreciably higher in the contoured area. This difference occurred notwithstanding the greatly increased vigor of plant-growth on the contoured area as evidenced by growth-observations and yield-data. The decreasing differences in moisture-content between the two areas from May until August is doubtless due, in a large measure, to the greater water-consumption of the more vigorous contoured plants.

By calculation from the data of Middleton, Slater, and Byers [2], it appears that a difference in moisture-content of one per cent represents approximately 0.40 inch of water in the three-foot profile on the Marshall soil. Thus in May, at the time of planting corn, the contoured area has averaged approximately 1.5 inches more available water than was present in the area planted in the direction of slope. Since the average moisture-content of the two areas was reduced to approximately the same level at the end of the season of most rapid plant-growth, it appears that all additional water saved by the contouring treatment during a 12-month period was utilized in the vigorous growth of a single succeeding crop. There is no evidence, in these data, of an accumulated increase in soil moisture-content over a period of years as a result of the contouring practice. There has been evidence of a distinct improvement in the growth and productivity of each crop.

Summary--Moisture-determinations on the Marshall silt-loam soil under various conservation-practices during three years of deficient rainfall are reported.

There is no evidence, under these conditions, of effect of direction of slope-exposure on the moisture-content of the three-foot surface-profile of the soil.

In the case of graded terraces the moisture-content under the channel was slightly higher and that of the middles slightly lower than the moisture-level observed in a similarly cropped area which was unterraced. Differences between the three conditions were very small. Soil under

terrace-ridges was consistently drier than at any other location studied.

A study of moisture-conditions under level terraces yielded results similar to those from the graded terraces discussed above. There appeared to be no appreciable amount of lateral movement of soil-moisture in the surface-layers.

The soil moisture-content was studied on two areas cropped continuously to corn, one having listed rows on the contour, while the other was listed in the direction of slope. The contoured area has consistently shown an appreciably higher moisture-content at the time of planting corn. This favorable balance continued, in decreasing amount, until the end of the period of rapid plant-growth. There is no evidence, in these data, of an accumulative increase in soil-moisture on the contoured area. There is evidence of distinct improvement in crop-growth and productivity as a result of the increased amount of soil-moisture available during the growing season.

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# SPECIFIC GRAVITY OF SEA-WATER AND THE GHYBEN-HERZBERG RATIO IN HAWAII

Chester K. Wentworth

Relations between fresh ground-water, both free basal and artesian basal, and sea-water around the coastal margins of islands of the Hawaiian group are controlled by the Ghyben-Herzberg principle. According to this principle the basal ground-water body in a simple, permeable oceanic island forms a biconvex lens, of which the deeply convex lower limit of fresh water reaches a depth approximately 40 times as far below sea-level as the upper limit or water-table lies above this datum. Thus the heights of the two balanced columns of fresh and salt water are related as in the following formula

$$1/(S.G. - 1) = D/H$$

where S.G. is the specific gravity of the sea-water at prevailing temperatures referred to fresh ground-water at its prevailing temperature, D is the depth of the bottom of the fresh-water lens (or zone of transition, or zone of balance) below sea-level, and H is the corresponding height of the fresh-water table, or artesian head, above sea-level, and (D/H) is the Ghyben-Herzberg ratio. This is a simple static relationship comparable to the balancing of two liquids in a U-tube, and can readily be demonstrated with fresh and salt water in any system where sand or other medium is used to prevent immediate convection and to retard diffusion. It is also precisely analogous to the principle of isostasy, as applied to segments of the crust of the Earth, and has been discussed adequately elsewhere [see 1 of "References" at end of paper]. It is evident from the formula that the Ghyben-Herzberg ratio, the ratio of depth below sea-level to height above it of the limits of fresh water, is a function, not of the specific gravity of the salt water, but of the difference between that of sea-water and that of fresh water. Small relative variations in the specific gravity of sea-water make much larger variations in the value of this excess of density, and the value commonly used in Honolulu for the specific gravity of sea-water, 1.025, is in reality indicated only to two significant figures so far as the excess is concerned.

Values used in the past for specific gravity or the derived Ghyben-Herzberg ratio have

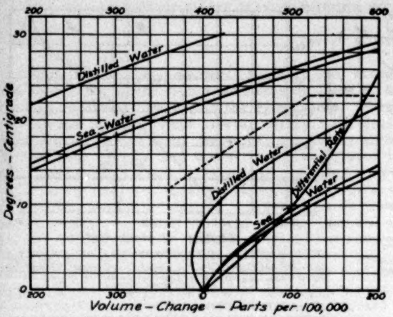

FIG. 1—RELATIVE VOLUME-CHANGES OF FRESH WATER AND SEA-WATER WITH TEMPERATURE-CHANGES (INSERT AT LOWER RIGHT FITS ON LEFT END OF DIAGRAM; DOUBLE LINE FOR SEA-WATER REPRESENTS EXTREMES OF SALINITY-VARIATION SOMEWHAT GREATER THAN THOSE ACTUALLY FOUND AT HONOLULU; VOLUMES REFERRED TO ARBITRARY DATUM AT 0°C)

either been general values taken from handbooks, or have been based on casual determinations on one, or but few, samples of sea-water. Confusion has existed also in regard to the temperatures of reference. Much oceanographic work on the specific gravity of sea-water is reported in reference to the density of distilled water at 4° C. Direct use of figures so reported may lead to errors in the Ghyben-Herzberg ratio of as much as ten per cent. Correction to comparable temperatures must take account of the fact that expansion of sea-water with rise in temperature takes place at a rate approximately one-fifth greater than that for fresh water through the range from 20° to 30° C (Fig. 1). Moreover, consideration must be given to the temperatures prevailing in the ground and in the ocean adjacent to the islands, in various zones below sea-level.

In an artesian area such as that at Honolulu, with static heads of 30 feet or more, and with deep wells some of which approach the zone of transition to salt water, it is a matter of considerable practical importance to know the local Ghyben-Herzberg ratio as accurately as possible. Only with such data can we compute the presumptive position of the zone of transition for various artesian heads, which may change by several feet with changing seasonal conditions.

Accordingly, in order to reconcile various conflicting assumptions as to the specific gravity of sea-water and the corresponding Ghyben-Herzberg ratios, as well as the assumptions for temperature used in making corrections in the past, a series of more than 100 samples of sea-water has been collected during the past year and specific gravities have been determined. The results of these measurements are summarized in Table 1; a more complete statement has been made elsewhere [2].

Table 1--Summary of determinations of specific gravity of sea-water near Honolulu

| | |
|---|---|
| Specific gravity, common surface-value, given in oceanographic literature, at about 27°, referred to distilled water at 4° C | 1.02300 |
| Specific gravity, at 27°/27°, average 77 shore-stations[a] | 1.02608[b] |
| Specific gravity, at 27°/27°, average 27 ship-stations[c] | 1.02608[b] |
| Specific gravity, corrected to 22°/22°, 104 determinations | 1.02633 |
| Specific gravity, corrected to reference with artesian water, average specific gravity 1.00023 | 1.02610 |
| Time-variations, same place (root-mean-square) | 0.00018 |
| Place-variations, same time (root-mean-square) | 0.00010 |
| P.E. (probable error), for duplication of field-samples | 0.000025 |
| P.E., for determinations in the laboratory on same sample | 0.000016 |
| P.E., of mean value, for whole series of 104 determinations | 0.000012 |
| Total solids, average, parts per million | 34,500 |

[a] Samples collected from a series of selected stations on rocky shores, chiefly on windward and leeward sides of southeastern Oahu.

[b] Each series of weighings of sea-water at about 27° in the laboratory was preceded and followed by similar weighing of distilled water in the same picnometer at the same temperature. Thus the picnometer was directly calibrated at each use, eliminating various corrections and assumptions.

[c] Samples collected by officers of vessels of Inter-Island Steam Navigation Company at various channel-points between Oahu and other islands of the Hawaiian Group.

In so far as average salinity and resulting density are concerned, the specific gravity is here determined probably within 0.00005 and the Ghyben-Herzberg ratio under the assumptions used is probably fixed to the nearest 0.1. Casual samples of sea-water are found to vary at various

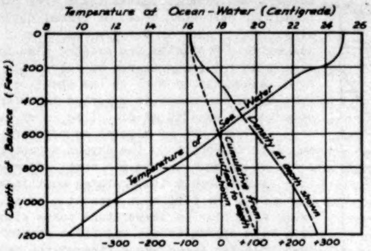

FIG. 2—TEMPERATURES AND RESULTANT LOCAL AND CUMULATIVE DENSITIES AT VARIOUS DEPTHS IN OCEAN IN VICINITY OF HONOLULU

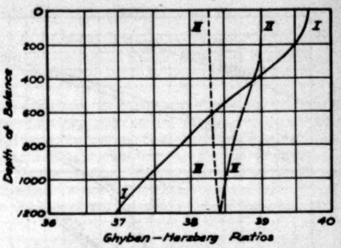

FIG. 3—GHYBEN-HERZBERG RATIOS AT VARIOUS DEPTHS ACCORDING TO THREE ASSUMPTIONS: (I) ARTESIAN WATER BALANCED AGAINST FREE OCEAN-WATER WITH PREVAILING TEMPERATURES AT VARIOUS DEPTHS; (II) UPPER HALF OF SEA-WATER COLUMN HAS TEMPERATURES OF FREE OCEAN AND LOWER HALF HAS TEMPERATURES FOUND IN ROCK; (III) BOTH SEA-WATER AND FRESH WATER ARE IN ROCK AND AT TEMPERATURES FOUND IN ARTESIAN BORE-HOLE

times from the mean by as much as 0.00030, at various placed from the general contemporary mean by about 0.00015. The variations from time to time are believed to be due to the mixing and churning of the known layers of ocean-water as currents and waves impinge on island-shores.

A more troublesome problem is encountered in deciding on the temperatures at which the fresh and salt waters should be compared. A few measurements carried through one year show that mean annual temperatures of basal water at sea-level at Honolulu approximate 21°70 C, with persistent local variations of 0°20. Artesian water from deeper levels is warmer; the modified geothermal gradient of deep underground waters approximates 0°5 C per 1000 feet. Annual variation of temperatures of water in deep wells is of the order of 0°02 to 0°05. For general purposes the temperature of 22° has been taken as standard for the fresh water. No simple condition for sea-water can be assumed. According to various structural relationships of the base of the artesian cap-rock, the slope and depth of the zone of transition, and the slope of the offshore bottom, the effective balancing column of salt water may be wholly part of the free ocean, or wholly in the permeable rock outside the zone of diffusion, or a combination of the two. Approximate temperature-conditions at various depths are shown in Figure 2, with resulting local and cumulative densities. These curves also take account of the differences in compressibility between sea-water and fresh water. The approximate volume-decrease per 100 feet of overlying water due to compression is, for sea-water, $132 \times 10^{-6}$, and for fresh water, $148 \times 10^{-6}$. Decrease in specific gravity of sea-water as referred to fresh water, at 1200 feet, is only 0.00009, and the correction is negligible at depths under 500 feet. Resulting Ghyben-Herzberg ratios corresponding to certain assumptions are shown in Figure 3.

It is concluded that for a single whole number for the Ghyben-Herzberg ratio, the value of 38 is best, especially since this is a closer approximation under various assumptions at greater depths, where errors in the ratio have greater absolute effect. Use of this value, in place of the 40, or 42, previously assumed, results in a change of the presumptive position of the zone of transition at Beretania Station from 1200 or 1260 feet below sea-level to only 1140 feet below sea-level. It is suggested that the margin of safety between bottoms of existing wells and deduced position of the zone of transition is substantially less than has been supposed.

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Honolulu, Territory of Hawaii

# ANALYSIS OF RUNOFF-PLAT EXPERIMENTS WITH VARYING INFILTRATION-CAPACITY

Robert E. Horton

Experimental data--Research Bulletin 280, Missouri Agricultural Experiment Station, gives the results of runoff plat experiments by Jesse H. Neal [see 1 of "References" at end of paper]. The same soil was used in all the experiments. This was Putnam soil, taken from the surface five to six inches, from a timothy meadow. The soil was placed in a tank 12 feet long, 3.63 feet wide, and 26 inches deep. Water was applied by an overhead sprinkling applicator. Neal states: "Before each run the soil was dried and cultivated to a depth of 4 inches . . . After the moisture-content of the surface four inches of soil had been reduced to between two-thirds and three-fourths of the capillary capacity, the surface-soil was leveled off and worked down to approximately the proper height. . . After the soil was approximately leveled off with a rake, a wooden templet was drawn the length of the box and all excess soil scraped off. Since the templet left the soil in a smooth condition, the rake was run lightly back and forth across the slope to simulate the condition of a good seed-bed. . . The surface-inch of soil was further dried to between one-fourth and one-half the capillary capacity before applying the rain." The rain was applied at intensities of approximately 4 inches, 3 inches, 2 inches, 1.5 inches, and 0.9 inch per hour, and the experiments were carried out with surface-slopes of 0, 1, 2, 4, 8, 12, and 16 per cent.

Soil-moisture determinations were made to depths of zero to one inch and zero to four inches before each experiment. The runoff, including solid matter, was measured in a tank at 10-minute intervals and the weight of solid material in the runoff was determined [for further details of methodology, see Neal's paper].

These experiments supply a set of data with the same soil and, as nearly as possible, the same surface-condition in each experiment but with varying rain-intensities and varying slopes. Neal has given infiltration-capacities for different time-intervals, determined by subtracting the net or water runoff from the total water applied. It was found that the infiltration-capacity decreased with time of application of water. These determinations do not, however, take into account the effect of surface-detention and give too high initial infiltration-capacities.

Neal found no consistent relation between surface-slope and infiltration-capacity. He did find, however, a fairly consistent relation between initial soil-moisture content and infiltration-capacity during the first ten minutes of rain. He has discussed at some length the relation of soil-losses to various factors and found a consistent relation between total soil-loss in pounds per inch of water applied, and the two variables, slope and rain-intensity.

Neal's experiments supply excellent data for determining the relation of infiltration-capacity to duration of application of rain and also for a study of various hydrologic factors affecting surface-runoff and erosion under conditions where the soil and soil-surface remain sensibly constant. They also show the variation which may be expected in such factors as depression-storage and maximum and minimum infiltration-capacity on small sample areas due to unavoidable variations in soil-condition. Presumably substantially the same variations would be encountered in different parts of a larger area, other things equal. It is probably true that the average of the experiments for a given slope and rain-intensity represent nearly the average condition which would pertain on a larger area with the same soil, soil-surface condition, slope, and rain-intensity.

In a previous paper [2] the author has given methods of analysis of runoff-plat experiments in cases where the infiltration-capacity remains sensibly constant from the start. The principal purpose of the present paper is to extend these methods to cases where, as in Neal's experiments, the infiltration-capacity decreased with duration of application of rain, ultimately becoming sensibly constant. The present paper is therefore supplemental to Bulletin 280 and covers somewhat different lines of analysis of the same experiments. The conclusions in the two papers do not in any way conflict. The author wishes to point out that the present paper is possible only because of the high quality and accuracy of Neal's experiments, as some of the methods used herein are sensitive and are vitiated by relatively minor errors in the experimental data. Professor Neal has kindly supplied data of measured runoff for different time-intervals in each experiment, together with time of beginning and ending of surface-runoff. These data have been used as a basis of the analyses in this paper.

Determination of varying infiltration-capacities from runoff-graphs--Referring to Figure 1, let $t = 0$ at the beginning of rain, $i$ = the rain-intensity in inches per hour, $q_s$ the surface-

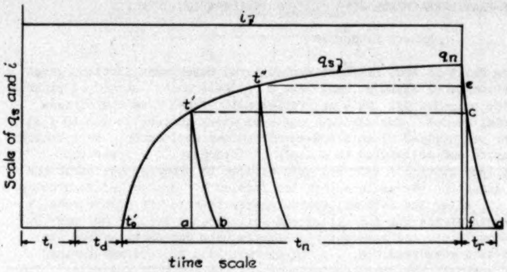


FIG.1 - DETERMINATION OF INFILTRATION - CAPACITY

runoff intensity, in inches per hour, at a given time t, $t_0'$ the time of beginning of runoff, $t_n$ the net duration of rainfall-excess or the time from the beginning of runoff to the end of rain, $t_r$ the duration of residual runoff.

At the time $t_0'$ the depression-storage is filled but there is no surface-runoff. At the end of $t_r$ there is again no surface-runoff and no surface-detention excepting depression-storage $V_d$, most of which still remains. Rainfall ends at the time $t_n$, and, in the interval $t_r$, runoff occurs from surface-detention only. It can be shown that for 75 per cent turbulent flow the amount of residual runoff is approximately

$$Q_r = (1/3)\, q_n t_r \tag{1}$$

where $q_n$ is the runoff-rate at time $t_n$. The average fraction of the area covered with surface-detention during residual runoff (exclusive of depression-storage on parts of the area from which runoff has ceased) is 1/3. The infiltration (with the same exception as to depression-storage) during residual runoff is the same as that from the entire area during a time interval $(t_r/3)$. Since the surface-detention $V_d$ is sensibly the same at the beginning and end of runoff, the total infiltration in the interval $(t_n + t_r/3)$ is $(P - Q)$, where P is the rainfall for the interval $t_n$ and $Q = (Q_n + Q_r)$. $Q_n$ is the total runoff to the time $t_n$. $Q_r$ is included since this runoff is derived from rain falling in the interval $t_n$. The average infiltration-capacity for the interval $(t\ + t_r/3)$ is

$$f_a = (P - Q)/(t_n + t_r/3) \tag{2}$$

Since $t_r$ is usually small relative to $t_n$, no large error results from neglecting $t_r$ in computing $f_a$.

Now suppose the rain had ended at some time t' preceding $t_n$. Then the average infiltration-capacity for the interval $t_0'$ to t' would again be

$$f_a = [P' - (Q' + Q_r'\ )]/[(t' - t_0') + t_r'/3] \tag{3}$$

The residual runoff-graph would have the same form as before but would start at a lower point on the hydrograph, and the value $Q_r'$ would be reduced by the area cfd (Fig. 1). Making this correction in $Q_r$, the average infiltration-capacity from the beginning of runoff to the end of any given time-interval can readily be obtained.

Similarly, the average infiltration-capacity for any time increment t' to t" between two sets of observations can be obtained by the equation

$$f = (\Delta P - \Delta Q)/[t'' - t' + (t_r'' - t_r')/3] \tag{4}$$

where $\Delta Q = (Q'' + Q_r'') - (Q' + Q_r')$, the values of Q being given and those of $Q_r$ determined in each case as above described. The values of $t_r'$ and $t_r''$ can be scaled from the residual runoff-graph, as, for example, fd = $t_r'$ on Figure 1. Except for early stages of runoff, the values of $(t_r'/3)$ and $(t_r''/3)$ are nearly the same. Assuming them equal, this term disappears by subtraction. It is only in computations of f for earlier stages of surface-runoff that the $(t_r/3)$ term is required. This method of computation of the average value of f for different time-increments has the effect of reducing the surface-detention, including depression-storage, to a constant amount $(V_d)$ at the beginning and ending of the time-increment, so that surface-detention need not be otherwise determined or taken into account.

A sample sheet of data and computations is given on Table 1. Column (2) gives the time-increments at the ends of which Q was observed. Columns (3), (4), and (5) give the increments of rainfall, the rain-intensity, and the mass-rainfall, respectively. Columns (6), (7), and (8), relating to soil-losses, are referred to later on. Columns (9), (10), and (11) give the runoff-increments, the runoff-intensity $q_s$ at the end of each time-interval, and the mass-runoff, respectively. Column (12) gives the increment of rainfall for the given time-interval. This is the same as column (3) excepting for the first-increment. For the first time-increment the rainfall is computed for the part of the increment during which runoff occurred. In this case $t_0 = 3$ minutes. ΔP is computed for 7 minutes. Column (13) equals the total runoff to the end of the given time-increment plus the residual runoff which would have occurred if rain had ended at the end of the given increment, or at the time shown on the same line in column (3); this is designated $Q_2'$. Column (14) gives the $\Delta Q_2'$ or the increment of runoff resulting from the rain which fell in the given time-interval. This is the difference between $Q_2'$ on a given line and that on the preceding line. Column (15) is the increment of total infiltration, F, for the given time-increment, obtained by subtracting the item in column (14) from that in column (12). This, in turn, divided by the time-increment, gives the average infiltration-capacity or the infiltration-capacity f at the mid-point of the given time-increment, as shown in column (16). Computation of the curve of f may be checked by computing $f_a$ for the entire runoff-interval by equation (2), then averaging the ordinates of the platted curve for the same time. The two quantities should be sensibly equal.

TABLE 1 ~ ANALYSIS OF NEAL'S EXPERIMENT NO. 9

| Slope | Time | Rainfall | | | Soil loss | | | Runoff | | | Computation of f | | | | | | | Q+F | $\delta_s$ | $\delta_a$ | $q_s$ | $\delta$ | $\delta w$ | V |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| % | Minutes | Δi In. | i i.p.h. | P In. | Δ lb. | Depth of Solid matter i.p.h. | Σ lb. | Δ In. | $q_s$ i.p.h. | Q In. | ΔP In. | $Q_2'$ In. | $\Delta Q_2'$ In. | ΔF In. | f i.p.h. | Comp'td f i.p.h. | F In. | In. | In. | In. | f.p.s. | In. | Sq. Ft. | f.p.s. |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) | (14) | (15) | (16) | (17) | (18) | (19) | (20) | (21) | (22) | (23) | (24) | (25) |
| 8 | 0 | 0 | 0 | 0 | 0[a] | 0[a] | 0[a] | 0[a] | 0[a] | 0[a] | 0[a] | 0 | 0 | 0 | | 1.30 | 0 | 0 | 0 | 0 | | | | |
| | 10 | .492 | 2.952 | .492 | 4.82 | .0826 | 4.82 | .248 | 2.125 | .248 | .344 | .254 | .254 | .090 | .675 | .72 | .076 | .324 | .020 | .072 | | | | |
| | 20 | Only total application for this expt given | ″ | .984 | 4.57 | .0548 | 9.39 | .431 | 2.586 | .679 | .492 | .693 | .439 | .053 | .318 | .35 | .100 | .779 | .057 | .109 | .0026 | .163 | .0489 | .053 |
| | 30 | | ″ | 1.476 | 4.00 | .0480 | 13.39 | .450 | 2.700 | 1.129 | ″ | 1.146 | .453 | .039 | .234 | .23 | .140 | 1.269 | .059 | .111 | .0027 | .166 | .0498 | .054 |
| | 40 | | ″ | 1.968 | 3.34 | .0401 | 16.73 | .451 | 2.706 | 1.580 | ″ | 1.598 | .452 | .040 | .240 | .21 | .175 | 1.755 | .065 | .117 | .0027 | .175 | .0525 | .051 |
| | 50 | | ″ | 2.460 | 3.40 | .0408 | 20.13 | .487 | 2.922 | 2.067 | ″ | 2.090 | .492 | 0 | 0 | .20 | .208 | 2.275 | .037 | .089 | .0029 | .134 | .0402 | .072 |
| | 60 | | ″ | 2.952 | 2.90 | .0348 | 23.03 | .464 | 2.784 | 2.531 | ″ | 2.548 | .458 | .034 | .204 | .20 | .241 | 2.772 | .032 | .084 | .0028 | .126 | .0378 | .074 |
| | 70 | | ″ | 3.444 | 2.87 | .0344 | 25.90 | .465 | 2.790 | 2.996 | ″ | 3.013 | .465 | .027 | .162 | .20 | .274 | 3.270 | .026 | .078 | .0028 | .117 | .0351 | .080 |
| | 80 | | ″ | 3.936 | 2.37 | .0284 | 28.27 | .432 | 2.592 | 3.428 | ″ | 3.442 | .429 | .063 | .378 | .20 | .307 | 3.735 | .053 | .105 | .0026 | .157 | .0471 | .055 |
| | 90 | | ″ | 4.428 | 2.25 | .0270 | 30.52 | .418 | 2.508 | 3.846 | ″ | 3.858 | .416 | .076 | .456 | .20 | .340 | 4.186 | .094 | .146 | .0025 | .219 | .0657 | .038 |
| | 100 | | ″ | 4.920 | 2.74 | .0529 | 33.26 | .453 | 2.718 | 4.299 | ″ | 4.317 | .459 | .033 | .198 | .20 | .373 | 4.672 | .100 | .152 | .0027 | .228 | .0684 | .040 |
| | 110 | | ″ | 5.412 | 2.40 | .0288 | 35.66 | .459 | 2.754 | 4.758 | ″ | 4.774 | .457 | .035 | .210 | .20 | .406 | 5.164 | .100 | .152 | .0027 | .228 | .0684 | .040 |
| | 120 | | ″ | 5.904 | 2.61 | .0313 | 38.27 | .443 | 2.658 | 5.201 | ″ | 5.215 | .441 | .051 | .306 | .20 | .439 | 5.640 | .116 | .168 | .0027 | .252 | .0756 | .036 |
| | 180 | | ″ | 8.856 | 14.55 | .0291 | 52.82 | 2.780 | 2.780 | 7.981 | 2.952 | 7.998 | 2.783 | .169 | .169 | .20 | .639 | 8.620 | .088 | .140 | .0028 | .210 | .0630 | .044 |
| | 183 | | | | .07 | .0028 | 52.89 | .017 | 0.340 | 7.998 | | | | | | | | | | | | | | |

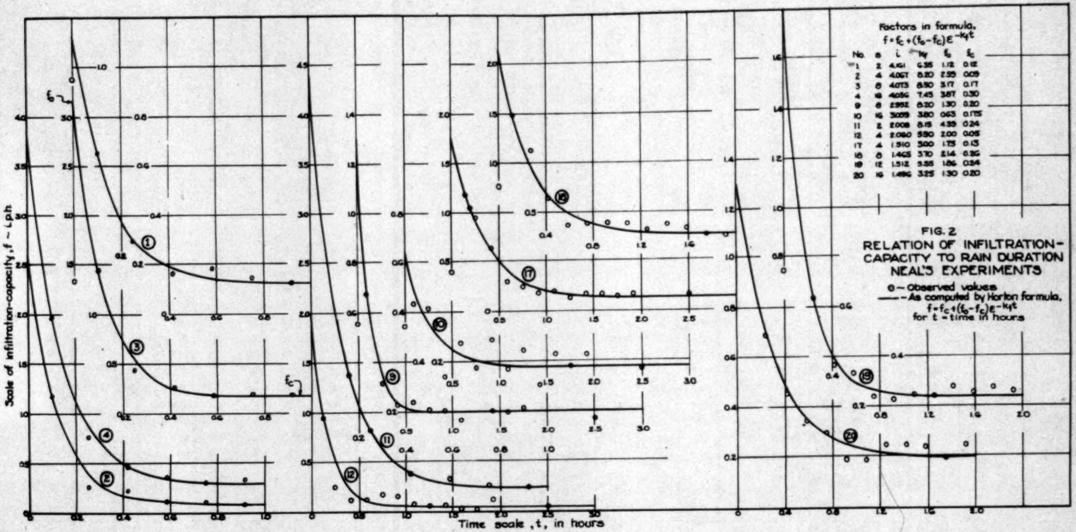
(a) Runoff commenced at 3 minutes

Relation of infiltration-capacity to rainfall-duration--As first noted by Horton [2] and subsequently by Neal [1], there is in general a decrease of infiltration-capacity during the early stages of a storm. Exceptions will occur: (1) Where the soil is already at its minimum infiltration-capacity; (2) in some regions, particularly on the western Great Plains, a moderate increase of infiltration-capacity has been noted [3] in the earlier stages of application of water to sprinkled plats. The increase occurred on areas subject to dust-storms and may have been due to washing away of fine dust deposited on the soil-surface and into the entrances to soil-pores.

There are at least three reasons why infiltration-capacity may decrease in the earlier stages of rain:

(1) Swelling of colloids and closing of soil-cracks and sun-checks.

(2) Inwashing of fine material to the surface-pores in the soil. Where surface-



Factors in formula,
$f = f_c + (f_0 - f_c)\varepsilon^{-k_f t}$

| No. | s | i | $k_f$ | $f_0$ | $f_c$ |
|---|---|---|---|---|---|
| 1 | 2 | 4.161 | 6.35 | 1.12 | 0.12 |
| 2 | 4 | 4.067 | 8.20 | 2.55 | 0.09 |
| 3 | 8 | 4.073 | 8.50 | 3.17 | 0.17 |
| 4 | 16 | 4.056 | 7.45 | 3.87 | 0.30 |
| 9 | 8 | 2.952 | 8.20 | 1.30 | 0.20 |
| 10 | 16 | 3.059 | 3.80 | 0.63 | 0.175 |
| 11 | 2 | 2.008 | 8.15 | 4.35 | 0.24 |
| 12 | 4 | 2.060 | 5.50 | 2.00 | 0.05 |
| 17 | 4 | 1.310 | 3.00 | 1.75 | 0.13 |
| 18 | 8 | 1.465 | 3.70 | 2.14 | 0.26 |
| 19 | 12 | 1.512 | 3.35 | 1.06 | 0.24 |
| 20 | 16 | 1.486 | 3.25 | 1.30 | 0.20 |

FIG. 2
RELATION OF INFILTRATION-CAPACITY TO RAIN DURATION
NEAL'S EXPERIMENTS

erosion occurs, water entering the soil-pores is charged with fine material in suspension, tending to clog the surface-pores. Even though the surface-soil is itself carried away, the clogging process still continues.

(3) Rain-packing--Especially in the earlier stages of intense rains, direct impact of raindrops on the soil compacts the soil-surface and decreases the infiltration-capacity. Except on flat areas, the soil-surface is not as a rule wholly covered except with a thin film of water during rain, and on the portions not more deeply covered, rain-packing continues until the soil-surface reaches a maximum density.

The first and third conditions partake of the nature of exhaustion-phenomena and apparently follow the law of diminishing returns or the inverse exponential law in some form.

The infiltration-capacities derived from typical graphs of Neal's data are shown by circles on Figure 2. It was impossible to cover the interval from $t = 0$ to $t_0'$, the beginning of runoff. However, the platted points apparently belong to curves which start at some finite value $f_0$ for $t = 0$. The infiltration-capacity then decreases as the duration of application of water continues, the value of $f$ approaching a constant minimum value $f_c$ asymptotically. These characteristics are common to exhaustion-phenomena and suggest that the curves corresponding to the platted points can be represented by a general equation of relation of infiltration-capacity to duration of rainfall of the form

$$f = f_c + (f_0 - f_c)e^{-K_f t} \tag{5}$$

where $f$ = infiltration-capacity, inches per hour, at time $t$, in hours; $f_0$ = initial infiltration-capacity at time $t = 0$; $f_c$ = minimum constant infiltration-capacity; $K_f$ is constant for a given curve. (This equation has been found to fit accurately the results of ring-infiltration experiments by Free, Browning, and Musgrave, and sprinkled-plat experiments on natural desert soils at Tucson, Arizona, by the United States Soil Conservation Service.)

The experiments give $f_c$ directly. To determine the other two constants, $f_0$ and $K_f$, the following method was used. Smooth curves were drawn to represent the platted points within the range for which they were determined. From each curve two pairs of values, $t_1f_1$ and $t_2f_2$, were taken off. Then from equation (5)

$$f_1 = f_c + (f_0 - f_c)e^{-K_f t_1} \tag{6}$$

$$f_2 = f_c + (f_0 - f_c)e^{-K_f t_2} \tag{7}$$

from which, by transposition

$$f_0 - f_c = (f_1 - f_c)e^{K_f t_1} = (f_2 - f_c)e^{K_f t_2} \tag{8}$$

The only unknown quantity in the two right-hand terms is $K_f$. The values of the second and third terms of equation (8) were computed for each of a series of assumed values of $K_f$ and the resulting numerical values of the second and third terms of equation (8) were platted in terms of $K_f$, as shown on Figure 3. The point of intersection of the smooth curves drawn through the two series of platted points gives at once the value of $K_f$ and also $(f_0 - f_c)$. Since $f_c$ is known, $f_0$ can then be determined.

On Figure 2 the solid lines were computed from equation (5), with the constants appropriate to each curve. Aside from obvious discordancies in the data in some cases, due to lack of details of variation in rain-intensity, there is good agreement between the platted points and the computed curves.

While equation (5) may not actually represent the law governing the physical processes involved, this equation is rational inform, since it not only represents the observed data within the range of observation but also gives results in agreement with known facts for the limiting or boundary conditions.

The values of $K_f$, $f_0$ and $f_c$, determined from the experimental data in conjunction with equation (5), are given in columns (4), (5), and (10) of Table 2.

Time required to attain constant infiltration-capacity--It will be noted that in all these experiments the infiltration-capacity becomes sensibly constant in the time ranging from one-half

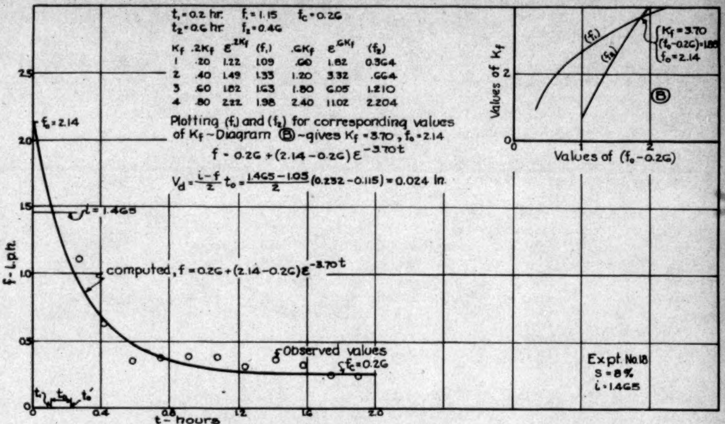


FIG. 3 - DETERMINATION OF CONSTANTS IN INFILTRATION-EQUATION AND COMPUTATION OF $V_d$

TABLE 2 ~ INFILTRATION-CONSTANTS - NEAL'S EXPTS.

| No. (1) | $i$ i.p.h. (2) | $s$ % (3) | $f_o$ i.p.h. (4) | $f_c$ i.p.h. (5) | $V_d$ In. (6) | $t_o$ hr. (7) | $\sigma_c$ i.p.h. (8) | $q_e/\sigma_c$ (9) | $K_f$ (10) | $m_o$ % (11) | $f_o'$ i.p.h. (12) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 4.161 | 2 | 1.41 | 0.12 | 0.147 | 0.050 | 4.041 | 0.992 | 6.35 | 11.8 | 0.72 |
| 3 | 4.073 | 8 | 3.42 | 0.17 | .048 | .042 | 3.903 | 1.002 | 8.50 | 13.5 | 2.62 |
| 2 | 4.067 | 4 | 2.87 | 0.09 | .067 | .042 | 3.977 | 1.006 | 8.20 | 12.8 | 1.97 |
| 4 | 4.036 | 16 | 3.87 | 0.30 | .026 | .042 | 3.736 | 0.961 | 7.45 | 10.5 | 1.88 |
|  | 4.084 |  | 2.89 | 0.17 | 0.072 | .044 |  | 0.990 | 7.62 |  | 1.80 |
| 8 | 3.101 | 4 | 2.29 | 0.09 | 0.068 | 0.050 | 3.011 | 0.980 | 12.20 | 19.9 | 2.04 |
| 10 | 3.059 | 16 | 0.63 | .17 | .123 | .050 | 2.889 | 1.002 | 3.80 | 20.7 | 0.71 |
| 6 | 3.030 | 1 | 3.27 | .16 | .030 | .050 | 2.870 | .993 | 7.10 | 19.5 | 2.65 |
| 7 | 2.993 | 2 | 3.03 | .20 | .040 | .083 | 2.793 | .992 | 5.65 | 12.1 | 2.08 |
| 9 | 2.952 | 8 | 1.63 | .20 | .080 | .050 | 2.752 | 1.011 | 8.20 | 19.7 | 1.44 |
|  | 3.027 |  | 2.17 | 0.16 | 0.068 | .057 |  | .996 | 7.39 |  | 1.78 |
| 12 | 2.060 | 4 | 2.25 | 0.05 | 0.021 | 0.058 | 2.010 | 0.971 | 5.90 | 19.8 | 2.21 |
| 14 | 2.026 | 16 | 2.53 | .28 | .019 | .067 | 1.746 | .973 | 6.35 | 12.6 | 1.87 |
| 13 | 2.017 | 8 | 4.40 | .25 | .001 | .021 | 1.767 | 1.008 | 6.80 | 10.9 | 1.97 |
| 11 | 2.008 | 2 | 4.39 | .24 | .014 | .050 | 1.768 | .991 | 8.15 | 11.5 | 2.70 |
|  | 2.028 |  | 3.39 | 0.20 | .014 | .049 |  | .986 | 6.80 |  | 2.19 |
| 19 | 1.512 | 12 | 2.49 | 0.24 | 0.010 | 0.050 | 1.272 | 0.974 | 5.55 | 13.4 | 1.52 |
| 17 | 1.510 | 4 | 1.75 | .13 | .011 | .075 | 1.380 | .972 | 3.00 | 16.4 | 1.77 |
| 16 | 1.503 | 2 | 1.48 | .16 | .078 | .217 | 1.343 | .936 | 2.75 | 18.6 | 1.42 |
| 20 | 1.496 | 16 | 1.53 | .20 | .040 | .150 | 1.296 | .953 | 3.25 | 13.6 | 1.09 |
| 15 | 1.484 | 1 | 1.57 | .18 | .040 | .158 | 1.304 | .919 | 3.20 | 17.4 | 1.66 |
| 18 | 1.465 | 8 | 2.14 | .26 | .023 | .117 | 1.205 | .954 | 3.70 | 11.6 | 1.33 |
|  | 1.495 |  | 1.81 | 0.19 | .034 | .128 |  | .951 | 3.57 |  | 1.46 |
| 22 | 0.900 | 8 | 2.28 | .23 | .004 | .117 | 0.670 | .956 | 4.60 | 22.0 | 2.56 |

hour to two hours. This time-interval is of great importance in relation to land-use and flood-control. For practical purposes f may be considered sensibly constant when it attains a value within one per cent of its final constant value. The time $t_c$ required can be determined as follows: Let $f = 1.01 f_c$. Then from equation (5)

$$f = 1.01\ f_c = f_c + (f_0 - f_c)e^{-K_f t_c}$$

or

$$f_c = 100\ (f_0 - f_c)e^{-K_f t_c}$$

and

$$t_c = (1/K_f)\ \ln 100(f_0 - f_c)/f_c \qquad (9)$$

Total or mass-infiltration--Given the constants $f_0$, $f_c$, and $K_f$, equation (5) provides a ready means of determining the total or mass-infiltration for any time-interval. Since

$$F = \int_0^t [f_c + (f_0 - f_c)e^{-K_f t}]\ dt \qquad (10)$$

or

$$F = f_c t - (1/K_f)\ (f_0 - f_c)e^{-K_f t} + \text{constant}$$

when $t = 0$, $F = 0$; therefore, constant $= (1/K_f)\ (f_0 - f_c)$

and

$$F = f_c t + (1/K_f)\ (f_0 - f_c)\ [1 - e^{-K_f t}] \qquad (11)$$

If there is a period $t_1$ of antecedent rainfall during which $i < f$, the computation of mass-infiltration by equation (11) must begin at the point where f and i become equal. To obtain the total infiltration from the beginning of rain there must be added to this the quantity $it_1$, or the infiltration for the period of antecedent rainfall, before depression-storage begins to fill.

Depression-storage--One of the facts brought out by these studies is that, with the exception of rain-intensities of three and four inches, the initial infiltration-capacity $f_0$ was usually greater than the rain-intensity i, so that there was a period of antecedent rainfall $t_1$ during which the soil absorbed the rain, and neither runoff nor depression-storage occurred. The time $t_1$ is that at which infiltration-capacity f and rain-intensity i become equal and can be taken directly from the f-curves. Using $t_d$ to represent the time required to fill depression-storage and $t_0'$ the time at which surface-runoff began, then when depression-storage begins to fill, $f = i$. When it is filled and runoff begins, or at the time $t_0'$, f has some value f'. The mean infiltration-capacity while depression-storage is filling is, approximately

$$(i + f')/2$$

The volume of depression-storage can therefore be computed in all cases by the equation

$$V_d = [i - (i + f')/2]\ t_d = (i - f'/2)\ t_d \qquad (12)$$

Column (6) of Table 2 contains the computed values of $V_d$. In general it is to be expected that depression-storage will decrease as slope increases, other things equal. The average values of the depression-storage for different slopes shown by these experiments are as follows:

| Slope in per cent | Number of experiments | $V_d$ in inches |
|---|---|---|
| 0 | . | ..... |
| 1 | 2 | 0.047 |
| 2 | 4 | 0.053 |
| 4 | 4 | 0.043 |
| 8 | 5 | 0.022 |
| 12 | 1 | 0.033 |
| 16 | 4 | 0.055 |

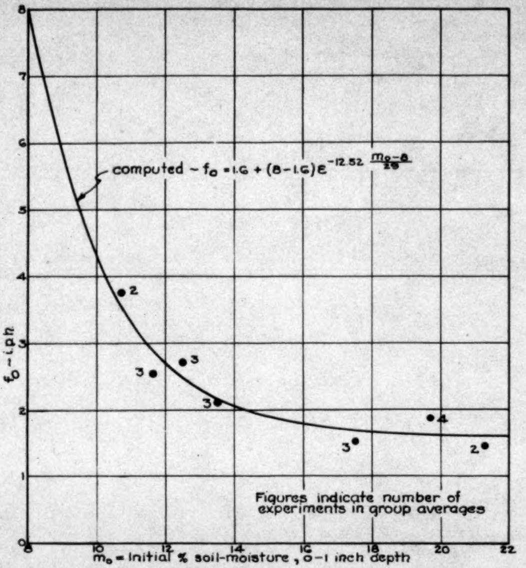


FIG. 4 - RELATION OF $f_o$ TO INITIAL SOIL-MOISTURE CONTENT AT 0-1 INCH DEPTH

For slopes of 2 to 12 per cent, the experiments show marked evidence of decrease of depression-storage with increasing slope. The high value of $V_d$ for slopes of 16 per cent is largely the effect of one abnormally high value of $V_d$. As a result the variation of depression-storage with slope is partly masked by residual errors.

Relation of infiltration-capacity to soil-moisture--Neal found a close correlation between his computed average infiltration-capacity for the first ten minutes of application of rain to the initial soil-moisture. The validity of his results are, however, affected by the fact that depression-storage and antecedent rainfall in which $f > 1$ were not taken into account. A better basis of comparison of infiltration-capacity with initial soil-moisture seems to be possible using $f_0$ as a comparate.

The initial soil-moisture to a depth of one inch, expressed in percentage of dry weight of soil, as given by Neal, was compared with the corresponding values of $f_0$, taking group-means of experiments with closely similar initial soil-moisture. The results are shown on Figure 4. The curve is closely similar to that obtained by Neal.

A similar platting of $f_0$ in terms of initial soil-moisture for a depth of one to four inches showed no definite evidence of correlation. This clearly indicates that the initial infiltration-capacity, at least, is primarily a function of the condition of the soil-surface.

The data on Figure 4 are well represented by the equation

$$f_0 = f_w + (f_d - f_w)e^{-K_m \frac{m_0-m_d}{m_w}} \qquad (13)$$

where $m_w$ is the moisture-content, per cent dry weight of the soil in its initial surface-condition but fully wetted (to field-moisture-capacity), $f_w$ is the infiltration-capacity of the soil in its

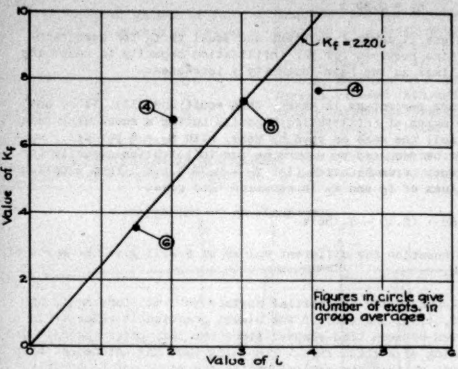


FIG. 5 – RELATION OF $K_f$ TO RAIN-INTENSITY, UNCORRECTED DATA, NEAL'S EXPTS. IN EQUATION, $f=f_c+(f_o-f_c)\varepsilon^{-K_f t}$

initial surface-condition but wetted at least to field-moisture-capacity, $m_d$ and $f_d$ are the moisture-content and infiltration-capacity, respectively, of soil in its initial condition when air-dry. $m_0$ and $f_0$ are, respectively, the actual initial moisture-content and initial infiltration-capacity. $m_w$ and $m_d$ correspond approximately to moisture-content at field-moisture-capacity and the hygroscopic moisture-content, respectively. Neal's experiments give $f_d$ = 8 i.p.h., $f_w$ = 1.6 i.p.h., $K_m$ = 12.52. The difference, $(f_d - f_w)$ = 6.4 i.p.h., is the maximum effect of drying out of the soil-surface for this soil and method of treatment.

Since the soil was the same and the surface-treatment was the same in different experiments, the observed variations in $f_0$ shown in column (4) of Table 2 are apparently due to (1) variation in soil-moisture, (2) uncontrolled differences in surface-compactness, (3) variation in rain-intensity. The effect of variation of initial soil-moisture can be largely eliminated by taking off from the curve on Figure 4 the values of $f_0$ for an assumed constant initial soil-moisture $m_0'$. For this purpose $m_0$ = 16 per cent was used. For 16 per cent soil-moisture the curve gives $f_0$ = 1.80 inches per hour. The observed values of $f_0$ were reduced to the basis of 16 per cent soil-moisture by assuming that the observed $f_0$ would have been changed by changing the initial soil-moisture content to 16 per cent in the same ratio that the corresponding values of $f_0$ on the curve are changed, or

$$f_0'/f_0 = f_a/f_b$$

where $f_0'$ is the initial infiltration-capacity reduced to the basis of 16 per cent soil moisture, $f_a$ is the value of $f_0$ given by the curve for the actual moisture-content, and $f_b$ = 1.80 inches per hour for 16 per cent moisture. Consequently

$$f_0' = 1.8\ (f_0/f_a) \tag{14}$$

The values of $f_0'$ or the initial infiltration-capacities for 16 per cent moisture are shown in column (12) of Table 2. Correction to 16 per cent moisture reduces the range and variability of $f_0$. The average of the observed values of $f_0$ is 2.24; the average of the values of $f_0'$ is 1.81; the average of the soil-moisture, zero to one inch, was 15.4 per cent.

The preceding discussion lays a foundation for the prediction of infiltration-capacity on a soil of the type and with the method of cultivation used in Neal's experiments. For a large area, with the same soil and cultivation, it may be assumed that the average of $f_c$ will apply in equation (5). From Table 2 this is 0.186; hence

$$f = 0.186 + (f_0 - 0.186)e^{-K_f t} \tag{15}$$

The constant $K_f$ is an exponential parameter which measures the time required for the infiltration-capacity to drop from its initial to its minimum value as the result of rain-packing and inwashing, particularly the former. It is presumable that the rate of rain-packing, and the consequent reduction of infiltration-capacity thereby, increases with rain-intensity, or the higher the rain-intensity, the shorter the time $t_c$ required to reduce the infiltration-capacity from that corresponding to initial soil-moisture, to the minimum value.

The larger the value of $K_f$ the shorter the time $t_c$. Hence $K_f$ should increase as the rain-intensity i increases. Neal's experiments afford an opportunity to test this hypothesis. The computed values of $K_f$ were averaged by groups for the different rain-intensities and the results have been platted on Figure 5. While not highly consistent, the data are well represented by the equation

$$K_f = 2.20\ i \tag{16}$$

This expression is rational in form, since it makes f constant and equal to $f_0$ for zero rain-intensity and, on the other hand, the time required for the infiltration-capacity to reach its minimum value $f_c$ approaches zero as a limit as the rain-intensity i increases.

If the initial surface soil-moisture percentage is known, then equations (13), (15), and (16) provide a means of predicting the march of infiltration-capacity during a subsequent rain. For example, let $i = 3.0$ i.p.h. for a soil the same as used by Neal, with $m_d = 8$ per cent, $m_w = 39$ per cent, and $f_w = 1.6$ i.p.h. Let it be required to determine the infiltration-capacity for an initial soil-moisture $m_0 = 12$ per cent. From equation (13) $f_0 = 2.70$ i.p.h. From equation (16) $K_f = 6.60$. Substituting these values of $f_0$ and $K_f$ in equation (15) gives

$$f = 0.186 + (2.10 - 0.186)e^{-6.60t}$$

for time t in hours. Solution of this equation for different values of t will give the march of infiltration during the subsequent rain.

Relation of $f_0$ to antecedent rain--Ordinarily the initial surface soil-moisture $m_0$ is unknown. In order to make equations (13), (15), and (16) of the utmost practicable value it is desirable to have some simple correlation between time elapsed since the last preceding rain and the surface soil-moisture at the beginning of a given rain. Presuming that the antecedent rain penetrated the soil to a sufficient depth so that the rate of drying out would not be greatly affected by moisture-condition below the depth of penetration, then it appears that at the end of the last antecedent rain, the surface soil-moisture would have been equal to the field-moisture-capacity $m_f$. At a time $t_1$ subsequent thereto the surface soil-moisture will be reduced by an amount dependent on the evaporation-rate. It appears probable that a fairly good correlation between initial moisture-content and time elapsed since the last preceding rain could be worked out but thus far this has not been done. Quite probably it is an inverse exponential law of a form

$$m_0 = m_h + (m_f - m_h)e^{-K_m t} \tag{17}$$

where $m_f$ = the field-moisture-capacity, $m_h$ = the hygroscopic moisture-capacity, and $m_0$ = moisture remaining at time t, and $K_m$ depends on the evaporation-rate.

It is possible that a simple linear equation

$$m_0 = m_f - (m_f - m_d)\ (t_1/t_d) \tag{18}$$

will meet practical requirements. In this equation $t_d$ is the time required for the soil-surface to become air-dry or to attain a condition of equilibrium with air of a given temperature and humidity. This is a function of the evaporation-rate but since there is a high degree of correlation between evaporation and air-temperature, and since temperature-data are much more commonly available than evaporation-data, it is possible that $t_d$ can be expressed with sufficient accuracy in terms of air-temperature alone.

Minimum infiltration-capacity--Normal minimum infiltration-capacity may be defined as the infiltration-capacity of a soil-surface free from sun-checks and biologic structures (perforations by earthworm, insect, and root) which has been wetted to field-moisture-capacity long enough to permit full swelling of colloids and adjustment of the soil-structure to a stable field-condition. The author has closely duplicated determinations of f in such soils in repeated experiments and hence concluded that a given soil has a definite normal minimum infiltration-capacity [4].

A given soil-surface may not fully meet these conditions during a rain because of under- or over-packing, puddling of the soil-surface and inwashing of fine material, or because of the presence of biologic structures. Some variation of $f_c$ in runoff-plat experiments is therefore to be expected.

The following tabulation shows the number of values of the constant or final infiltration-capacity lying between given limits. For most of the experiments $f_c$ lies between 0.15 and 0.30 and the variations from the average value $f_c = 0.186$ may apparently be attributed to differences in compactness of the soil, as it is known that infiltration-capacity is sensitive to variation of soil-porosity.

Distribution of values of $f_c$

| Limits | Number of values |
|---|---|
| < 0.10 | 3 |
| >0.10 < 0.15 | 2 |
| >0.15 < 0.20 | 5 |
| >0.20 < 0.25 | 6 |
| >0.25 < 0.30 | 4 |

Compared with $f_0$, the variation of minimum infiltration-capacity of a given soil is confined to a relatively narrow range. Also it is to be noted that the minimum initial infiltration-capacity for loose soil, uncompacted by rain but fully wetted, as shown by Figure 4, is 1.6 inches per hour. The difference between this and 0.186 inch per hour, the average minimum $f_c$ after prolonged rain, may be attributed to rain-packing or inwashing, or both.

Characteristics of hydrographs--The hydrographs or runoff-graphs for several of Neal's experiments are shown on Figures 6, 7, and 8. These hydrographs were drawn through all of the ob-

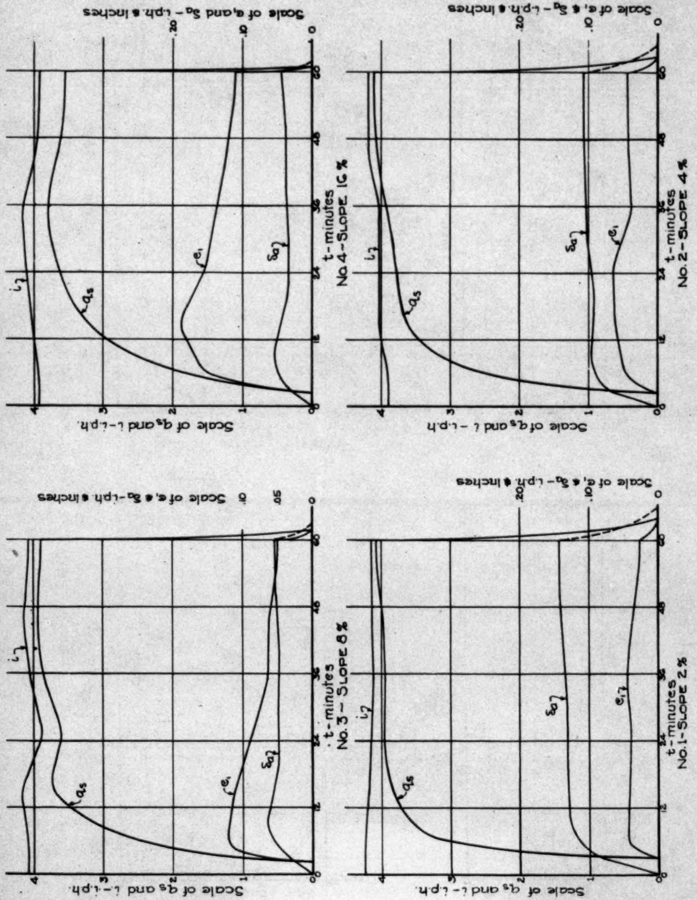
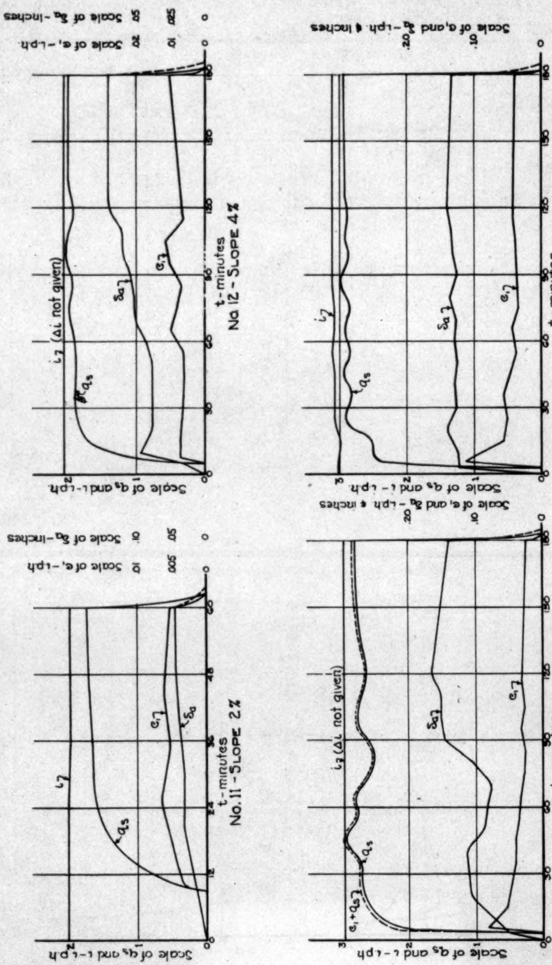


FIG. 6 -ANALYSIS OF NEAL'S EXPERIMENTS, i = 4.00 i.p.h.

served points. They show in many instances distinct waviness, especially after the flow became stable. The presence or absence of waviness does not appear to be closely related either to the slope or rainfall-intensity. The fact that the wave-crests are usually 20 minutes or more apart, shows that these are not true rain wave-trains but that the waviness is due to alternate building up and breaking down of debris-dams on the soil-surface or to successive stages of initiation of gullies and consequent concentration of runoff [5]. Another characteristic of these hydrographs is the occurrence of relatively abrupt fronts in most instances. Because of this condition it



No. 9 - SLOPE 8%

No. 10 - SLOPE 16%

No. 11 - SLOPE 2%

No. 12 - SLOPE 4%

FIG. 7 -ANALYSIS OF NEAL'S EXPERIMENTS, $i$ = 2 AND 3 i.p.h.

has been found impracticable except in a few cases to determine completely the law of overland-flow. Using the curves of infiltration-capacity for the same experiments (Fig. 2), the increments of surface-detention $\Delta\delta_a$ have been determined for successive time-increments $t_2 - t_1$ by the equation

$$\Delta\delta_a = i_a (t_2 - t_1) - [(Q_2 - Q_1) + f_a (t_2 - t_1)] \tag{19}$$

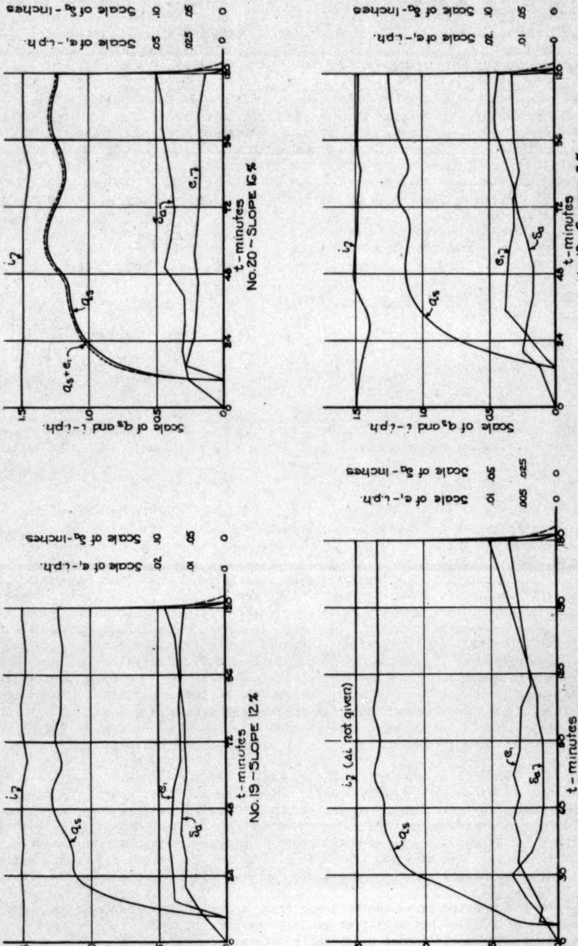


FIG. 8 ~ANALYSIS OF NEAL'S EXPERIMENTS, $i$ = 1.5 i.p.h.

where $Q_2$ and $Q_1$ are the total runoff at times $t_2$ and $t_1$, from the observational data, $i_a$ and $f_a$ are the average rain-intensities and average infiltration-capacities for the given time-interval. By summation of values of $\Delta\delta_a$ the average detention-lines shown on Figures 6, 7, and 8 have been obtained. Neal has furnished the amounts of erosion in pounds on the 0.001-acre plat for each 10-minute time-interval. The erosion-rates for different time-increments were reduced to the basis of depth $e_1$ of the solid matter removed from the soil-surface in inches per hour. The specific gravity of the soil-material was 2.3, and the weight of a cubic foot of solid soil-material was 144 pounds. Hence for a 0.001-acre plat the rate $e_1$, in inches per hour, is

$$e_1 = 12/(144 \times 43.56) \times (\text{pounds per hour}) = 0.00192 \times (\text{pounds per hour}) \qquad (20)$$

Lines showing the erosion-rate $e_1$ have been added to Figures 6, 7, and 8.

In this connection it is suggested that the unit "inches depth per hour" of removal of solid matter is preferable to other units sometimes used in expressing erosion-rates from the ground-surface, since it does not involve the volume-weight of the soil, which varies for different soil-conditions, and thus enables experiments on different soils or on the same soil under different conditions to be directly compared. Furthermore, the quantity $e_1$ when added to the rate of flow of water $q_s$ gives the total rate of runoff of water and soil combined. For illustration, lines showing $(q_s + e_1)$ have been added to the hydrographs for experiments numbers 9 and 20.

Measuring devices for stream-channels measure the total flow (solids plus fluid). Volume-concentration of suspended matter can advantageously be used in this case also. If $w_1$ is the weight of silt per unit-volume of flow, and G = specific gravity of suspended solids, then

$$C_{vol} = Gw_1/q \qquad (21)$$

The total volume of suspended matter, $S_1$, carried by a given measured volume of the total flow q per unit of time is, then

$$S_1 = qC_{vol} \qquad (22)$$

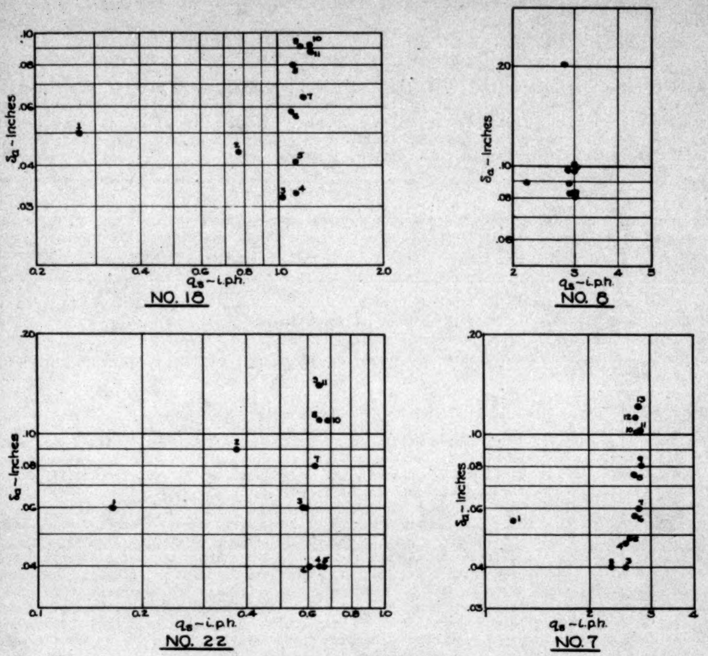
The author has elsewhere shown that for various types of steady hydraulic flow (without bore-fronts or mud-flows) there is a definite relation of runoff-intensity $q_s$ and average detention-depth $\delta$ near the outlet end of a runoff-plat [6]. This relation is expressed by the equation [7]

$$q_s = [(M + 1)/M]\, K_s \delta_a^M \qquad (23)$$

This relation applies to some of Neal's experiments but to most of them it apparently does not apply. Three examples of the relation of $q_s$ to $\delta_a$ are shown on Figure 9. Numbers indicate the sequence of the 10-minute intervals for which the values of $q_s$ and $\delta_a$ were determined. In each instance the initial point (No. 1) indicates a flow rate $q_s$ much below that for stable flow. This, combined with the abrupt fronts of many of the hydrographs, suggests that in these cases runoff started with a miniature mud-flow similar to the debris-dams often occurring at the fronts of cloudburst-floods in mountain canyons. The high frictional resistance of the mud-front cuts down the velocity much below that for normal hydraulic flow at the same depth. Figure 9 also shows that the discharge-rate $q_s$ became nearly constant except for the first and second intervals and was thereafter independent of the depth $\delta_a$ of surface-detention. It will be noted that the points with the same $q_s$ and $\delta_a$ occur in pairs for successive time-intervals. A condition of flow independent of depth can occur hydraulically in conjunction with a constant volume of flow passing through a reach of a stream in which a back-water curve exists. Back-water curves behind debris-dams in case of floods in canyons are not of uncommon occurrence.

The back-water curve in a permanent stream-channel remains stationary relative to an observer on the bank. If an observer travels along the stream and takes stage-, velocity-, and discharge-observations, he will find: (1) The volume of flow is constant; (2) there is no correlation of flow-rate to stream-stage; (3) since q = constant = $\delta$wv, if the width w is constant, then the velocity v will vary inversely as the depth $\delta$. These conditions remain true even though the flow actually follows, for example, the Manning formula. The reason for these seeming anomalies is that the observations taken are not those required to reveal the true laws of flow.

In case of the back-water curve behind a mud-flow, a stationary observer taking observations as the back-water curve passes him will find exactly the same things. It is evident that in such cases the law of surface-runoff cannot be directly determined from the observations.



NO. 18

NO. 8

NO. 22

NO. 7

FIG. 9—RELATION OF AVERAGE DETENTION-DEPTH TO RUNOFF-INTENSITY (WATER ONLY); NEAL'S EXPERIMENTS

The occurrence of points in pairs on Figure 9 indicates that the degradation of the soil-surface takes place by more or less abrupt jumps or quanta. In most cases the second of a pair of adjacent points shows both higher stage ($\delta_a$) and larger flow ($q_s$). If two of these points are connected by a line, its slope will be found to be usually between 5/3 (fully turbulent flow) and 2.33 (50 per cent turbulent), indicating that, during a given stage, the flow was in accordance with equation (23). It appears probable that in Neal's experiments, lack of direct relationship of $q_s$ to $\delta_a$ is, in part at least, the result of successive formation and breaking of debris dams or divides between depressions, accompanied by abrupt changes of $\delta_a$ without a corresponding change of $q_s$, due to successive stages of gullying. Even then the fact that $\delta_a$ progressively increased during a given experiment without a corresponding increase of $q_s$ remains to be accounted for. This may be due to the fact that on the ungullied portion of the plat, the detention-depth remained nearly as great as without the gullies. As a gully forms, a high concentration of suspended matter builds up either a debris-dam near the outlet or a mud-flow in the gully, behind which back-water accumulates. This increases the average detention without a corresponding increase of $q_s$.

The hydrographs on Figures 6, 7, and 8 are platted in terms of water-flow only. The abrupt fronts of many of the hydrographs may be due to initial mud-flow, with abrupt release of water as the mud passed the outlet sill of the runoff-plat. These abrupt fronts are, however, due in a considerable degree to the variation of infiltration-capacity f. A decrease of f with time has the same effect on the form of the hydrograph as a corresponding increase of rain-intensity with constant f.

The author has elsewhere given the semi-rational equation of the rising side of the hydrograph [8]

$$q_s = \sigma \tanh^M \ [(M + 1)/M] \ (\sqrt[M]{\sigma K_s}) t \tag{24}$$

where $\sigma$ = the supply-rate (i - f), $K_s$ and M are the coefficient and exponent, respectively, in the surface-runoff equation (23), t is time in hours, and $q_s$ the runoff-intensity in inches per hour. This equation is rational for 75 per cent turbulent flow ($M = 2$) and closely approximative of other types of flow from 50 per cent laminar ($M = 2.33$) to fully turbulent ($M = 5/3$). The degree of turbulence is related to M through the equation

$$I = (3/4)\ (3.0 - M) \tag{25}$$

Equation (24) applies, however, only with a constant supply-rate $\sigma$. For an increasing supply-rate, as with a decreasing infiltration-capacity and constant rain-intensity, the supply-rate can be assumed constant and equal to its average value in each of a series of short successive time-intervals.

Let the supply-rates for interval 0 to $t_1$, $t_1$ to $t_2$, etc., be designated $\sigma_1$, $\sigma_2$, etc. For interval 1, $\sigma_1$ in equation (24) gives the required values of $q_s$ ending with $q_1$ at $t_1$. If the supply-rate had been $\sigma_2$ from the start, then at the end of some time-interval $t_1'$, $q_s$ would equal $q_1$ and $t_1'$ can be determined from equation (24) by making $q_s = q_1$ for $t = t_1'$ and $\sigma = \sigma_2$, and solving for $t_1'$, giving

$$t_1' = [M/(M + 1)]\ [1/\sqrt[M]{\sigma_2 K_s}] \tanh^{-1} (\sqrt[M]{q_1/\sigma_2}) \tag{26}$$

If, now, $q_s$ is computed for a series of times $t_1' + \Delta_1$ $t_1' + \Delta_2$, etc., to $t_1' + (t_2 - t_1)$, using $\sigma_2$ in equation (24), the resulting values of $q_s$ will be the correct values for the times $(t_1 + \Delta_1)$, $(t_1 + \Delta_2)$, etc. to $t_2$. In this way the arcs of the hydrograph can be computed and filled in for successive time-intervals, with different supply-rates [10].

Calculations have been made, as shown on Figure 10 of three runoff-graphs, with $K_s = 10$ and for 75 per cent turbulent flow. Line A shows the runoff-graph with the infiltration-capacity decreasing with duration of rain, in the manner shown by the average of Neal's experiments. Line B shows the runoff-graph with the infiltration-capacity constant and equal to the average value (f = 1.36 i.p.h.) shown by Neal's experiments. Line C shows the runoff-graph for the infiltration-capacity constant and equal to the average minimum value (f = 0.186 i.p.h.) shown by Neal's experiments. In all cases the rain-intensity i = 4 i.p.h. is constant. The area between lines A and C shows the reduction of surface-runoff resulting from a high initial infiltration-capacity as compared with the constant infiltration-capacity $f_c$. The ultimate runoff-intensity is, however, the same in both these cases. Lines A and B show that initially high infiltration-capacity materially reduced the runoff in the first 0.2 hour as compared with a constan infiltration-capacity equal to the average, but after 0.2 hour the infiltration-capacity fell below the average, and both the total runoff and the runoff-intensity are greater than for a constant infiltration-capacity.

A further point to be noted is that, as shown by line A, with varying infiltration-capacity the front of the hydrograph is much more abrupt than for an equal constant average infiltration-capacity. Line B differs, however, from most of Neal's experiments and many other experiments where erosion occurred, in that the front of the hydrograph B starts gradually with slope zero at time t = 0, whereas in Neal's and many other hydrographs where high initial erosion takes place, the front of the hydrograph has a vertical slope. This difference indicates at once that in these hydrographs the abrupt fronts are in the main due to mud-flow.

Soil-erosion--It is to be noted that the first measurement of erosion-rate was at the end of ten minutes' rain. Many of the experiments, for example, numbers 3, 4, 9, and 10, show maximum erosion-rates for the first 10-minute interval.

Erosion-concentration may be designated $C_{vol}$ and defined as the ratio of solid material in the runoff to the total runoff, including both water and solid material, or, for a given time-interval

$$C_{vol} = e_1/(e_1 + q_s) \tag{27}$$

If only solid matter was carried away, $q_s$ would be zero and $C_{vol}$ would be unity. The erosion-

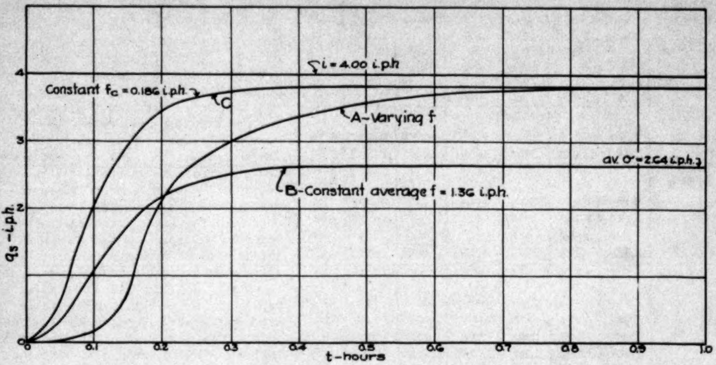


FIG. 10-EFFECT OF VARYING INFILTRATION-CAPACITY ON RUNOFF-GRAPH

concentration for one of Neal's experiments is shown on Figure 11. The high initial concentration of solid matter suggests that in these experiments the initial loss of soil-material was largely due to rain-impact preceding or in the early stages of runoff--a condition compatible with the occurrence of miniature mud-flows.

Other experiments yield similar but not always consistent relation curves of $C_{vol}$ to t. Erosion-concentration starts at a high value $C_0$ and approaches a constant value $C_c$ asymptotically. The constants in the equation

$$C_{vol} = C_c + (C_0 - C_c)e^{-K_c t} \tag{28}$$

can be evaluated by the same method as for infiltration-capacity curves in Figure 3. The identity of form of curve and form of equation for erosion-concentration-time and for infiltration-capacity-time (Fig. 2) suggests that reduction of erosion-concentration with duration of runoff is the result of one or more of the same factors which produce reduction of f. Rain-impact is probably responsible for the high initial concentration $C_{vol}$ but rain-packing and adhesion from

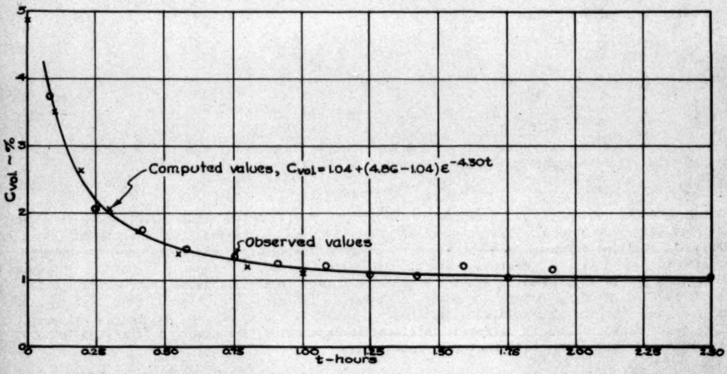


FIG. 11-RELATION OF VOLUMETRIC CONCENTRATION OF SEDIMENT TO DURATION OF RAIN, NEAL'S EXPT. NO. 9.

TABLE 3 - SOIL-EROSION CONSTANTS - NEAL'S EXPTS

| No. | S<br>% | $i$<br>i.p.h. | $q_s$<br>i.p.h. | $S_a$<br>In. | V (a)<br>f.p.s. | $e_1$<br>i.p.h. | $e_1'$<br>i.p.h. | $C_{vol.}$<br>% |
|---|---|---|---|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
| 6 | 1 | 3.028 | 2.793 | 0.119 | 0.057 | 0.0096 | 0.0749 | 0.34 |
| 15 | 1 | 1.453 | 1.172 | .059 | .046 | .0020 | .0027 | .17 |
|  |  | 2.240 | 1.983 | .089 | .052 | .0058 | .0388 | .25 |
| 1 | 2 | 4.145 | 3.949 | 0.137 | 0.064 | 0.0383 | 0.3973 | 0.96 |
| 7 | 2 | 3.028 | 2.768 | .093 | .072 | .0133 | .1019 | .48 |
| 11 | 2 | 1.998 | 1.687 | .042 | .090 | .0060 | .0171 | .35 |
| 16 | 2 | 1.494 | 1.267 | .098 | .029 | .0022 | .0035 | .17 |
|  |  | 2.666 | 2.418 | .092 | .064 | .0149 | .1799 | .49 |
| 2 | 4 | 4.100 | 3.905 | 0.103 | 0.084 | 0.0497 | 0.7578 | 1.26 |
| 8 | 4 | 3.092 | 2.977 | .100 | .070 | .0247 | .2189 | .82 |
| 12 | 4 | 2.085 | 1.949 | .053 | .086 | .0080 | .0304 | .41 |
| 17 | 4 | 1.512 | 1.339 | .018 | .207 | .0058 | .0104 | .43 |
|  |  | 2.690 | 2.542 | .068 | .112 | .0220 | .2544 | .73 |
| 3 | 8 | 4.069 | 3.811 | 0.050 | 0.170 | 0.0760 | 1.1038 | 1.96 |
| 9 | 8 | 2.952 | 2.719 | .122 | .053 | .0341 | .2521 | 1.24 |
| 13 | 8 | 2.016 | 1.651 | .008 | .069 | .0215 | .0586 | 1.28 |
| 18 | 8 | 1.483 | 1.147 | .064 | .045 | .0133 | .0175 | 1.15 |
| 22 | 8 | 0.900 | 0.641 | .009 | .215 | .0030 | .0123 | 0.47 |
|  |  | 2.284 | 1.994 | .051 | .110 | .0296 | .2889 | 1.22 |
| 19 | 12 | 1.502 | 1.247 | 0.068 | 0.041 | 0.0140 | 0.0218 | 1.11 |
| 4 | 16 | 4.057 | 3.601 | 0.038 | 0.216 | 0.1431 | 1.8556 | 3.83 |
| 10 | 16 | 3.096 | 2.904 | 132 | .049 | .0427 | .3601 | 1.45 |
| 14 | 16 | 2.023 | 1.681 | .079 | .047 | .0453 | .1280 | 2.62 |
| 20 | 16 | 1.485 | 1.234 | .083 | .033 | .0187 | .0285 | 1.49 |
|  |  | 2.665 | 2.355 | .083 | .086 | .0624 | .5930 | 2.35 |

(a) As given in Col. 6, $v = \frac{q_s}{S_a}$. These are relative quantities, not the true mean velocities on the plat.

wetting and swelling of colloids appear to be the main factors tending to reduce erosion-concentration. Thus rain-intensity appears to operate in two opposite ways: At the beginning of rain, high intensity induces high erosion-concentration but after a few minutes the increased rain-packing checks the erosion-rate and reduces the concentration. This is partly because of decrease of the infiltration-capacity f and consequent increased runoff-intensity $q_s$. In view of the open question as to how much of the observed soil-erosion was due to rain-impact and how much was due strictly to surface-runoff, it has seemed desirable to attempt to study these two effects separately. For this purpose Table 3 was compiled. This shows various factors for each experiment for the interval during which the runoff was sensibly constant, including the rate of soil-removal $e_1$, the corresponding rate of flow, and the depth of surface-detention and velocity of overland-flow, both near the outlet end of the plat.

The author has made an analysis of erosion-rate in terms of $q_s$, like that made by Neal in terms of rain-intensity i. This shows erosion-intensities varying as some power of $q_s$ or i a little greater than the square. Logarithmic platting in terms of $q_s$ shows an exponent of $q_s$ so close to 2 that the statement may fairly be made that for the conditions and within the limits of Neal's experiments, the erosion-rate for stable flow varies nearly as the square of the runoff-intensity. The author finds

$$e_1 = S^{5/8}\, q_s^2 \qquad (29)$$

Neal [1] found

$$E \text{ (pounds per acre per hour)} = 0.4\, S^{0.7}\, i^{2.2} \qquad (30)$$

The difference in the exponents 2.2 and 2.0 for i and $q_s$ is probably due to the fact that for stable flow-conditions the infiltration-capacity was nearly constant and equal to $f_c$, so that $q_s = (i - f_c)$.

Equations (29) and (30) are empirical and require confirmation before application to other soils or other conditions. This is especially true in view of the fact that in many of the experiments gullying occurred, and the equation may not be applicable to conditions of pure sheet-erosion without gullying. Exclusive of initial erosion due to rain-impact, there is no necessary relationship between rain-intensity and erosion-rate, and it seems obvious that Neal's equation cannot be applied to conditions where the infiltration-capacity was different from that in his experiments. For example, in Neal's experiments, with i = 4.0 i.p.h., $q_s$ was approximately 3.8 i.p.h. For other soils with different infiltration-capacities, the same runoff-intensity might have resulted with widely different rain-intensities.

The question arises whether for a given soil and surface-conditions, erosion-rate can better be expressed in terms of the two variables, runoff-intensity $q_s$ and slope S, or in terms of detention-depth $\delta_a$ and velocity of overland-flow $v_0$. The latter appear to be the more direct variables controlling erosion-rate; also they take into account the effect of slope. Probably because of gullying and the formation and breaking down of debris-dams, the author has not found a satisfactory relationship from Neal's experiments between either erosion-rate and depth of surface-detention or between erosion-rate and velocity of overland-flow.

This discussion of erosion is merely a preliminary approach to the analysis of this complex problem. It seems desirable that experiments primarily to determine infiltration-capacity f and the law of overland-flow should be segregated from those intended to determine erosion-phenomena. In the former the rain-intensity must exceed f but should be kept below that producing active erosion; in the latter the rain-intensity should be above the critical value to initiate erosion. But there are two cases which should be studied separately: (1) Pure sheet-erosion without gullying; (2) erosion where gullying occurs. This can in general be accomplished by the use of a rain-applicator capable of producing a sufficiently wide range of rain-intensities without too large gaps between successive intensities.

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[1] Jesse H. Neal, The effect of the degree of slope and rainfall characteristics on runoff and soil erosion, Res. Bull. 280, Missouri Agric. Expt. Sta., April 1938.
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[3] From unpublished experiments.
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[5] Robert E. Horton, Rain wave-trains, Trans. Amer. Geophys. Union, 1938, pp. 368-374.
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[7] This equation differs from one elsewhere given in that $q_s$ is expressed in terms of average detention-depth $\delta_a$ instead of detention-depth $\delta$ near the outlet. The quantities $\delta$ and $\delta_a$ are connected by the relation $\delta = [(M + 1)/M]\,\delta_a$.
[8] Robert E. Horton, The interpretation and application of runoff plat experiments with reference to soil erosion problems, Proc. Soil Sci. Soc. Amer., v. 3, 1938.
[9] The subject of the equation of the hydrograph with varying supply-rates has been treated analytically by the author for both increasing and decreasing supply-rates. The results will be published elsewhere.

Voorheesville, New York

## THE RELATION OF RAINFALL TO ELEVATION IN THE SOUTHERN APPALACHIAN REGION

David E. Donley and Richard L. Mitchell

An investigation of the relation of elevation to the variation in annual rainfall at a number of rainfall-stations in western United States was made about 1899 by Mr. J. B. Lippincott [see 1 of "References" at end of paper]. This study was extended by Dr. Daniel W. Mead [2] in 1919 so as to include additional stations in Europe and the United States. These investigations indicated rather conclusively that in most mountain areas the amount of mean annual rainfall was greater, the higher the elevation of the station considered.

At the time these studies were made, practically no data were available for the higher sections of the Appalachian Mountains, and this region could not be included in the areas considered. Collection of rainfall-data for the higher parts of the Southern Appalachian Region was inaugurated by the Tennessee Valley Authority in 1934 as a part of its investigation of the water-resources of the Tennessee River Basin and is still being carried on by that agency.

There are now 84 rainfall-stations located at or above an elevation of 2500 feet above mean sea-level, and continuous records are available for 73 of these for the period October 1, 1935, to September 30, 1938. These records have been carefully analyzed with a view to determining what relation exists in this Southern Appalachian Region between the amount of mean annual rainfall and the elevation of the stations at which it is recorded. The results of this analysis are presented herewith.

Geographical location of the Region--The upper half of the Tennessee River Basin drains about 10,000 square miles of the Great Smoky and the Blue Ridge Mountains lying in Virginia, North Carolina, Tennessee, and Georgia. These mountains extend in a general direction from

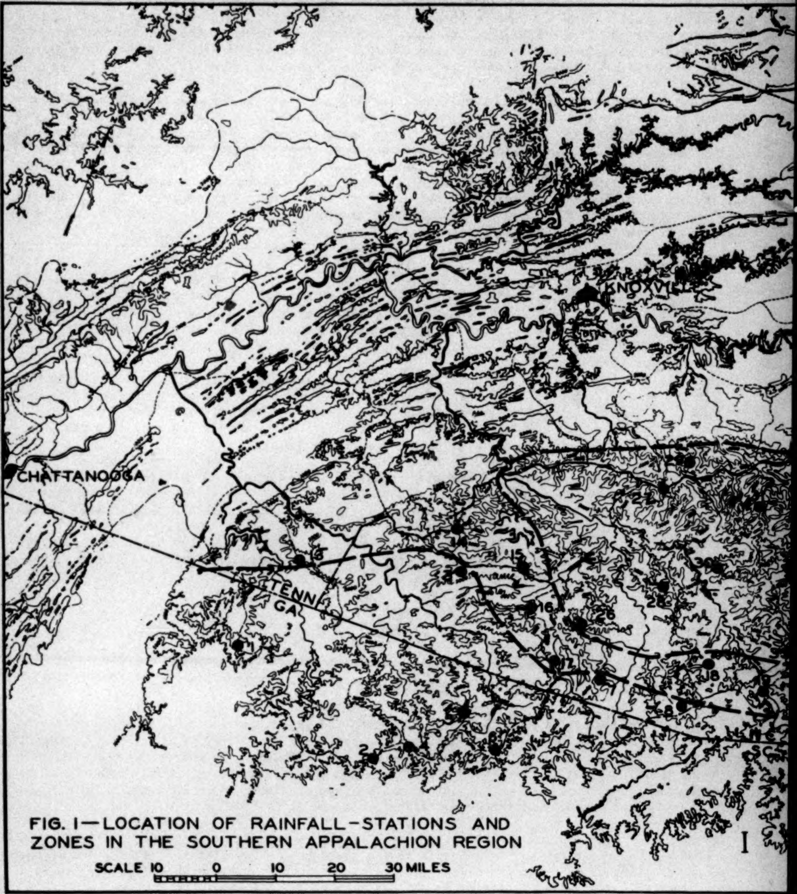
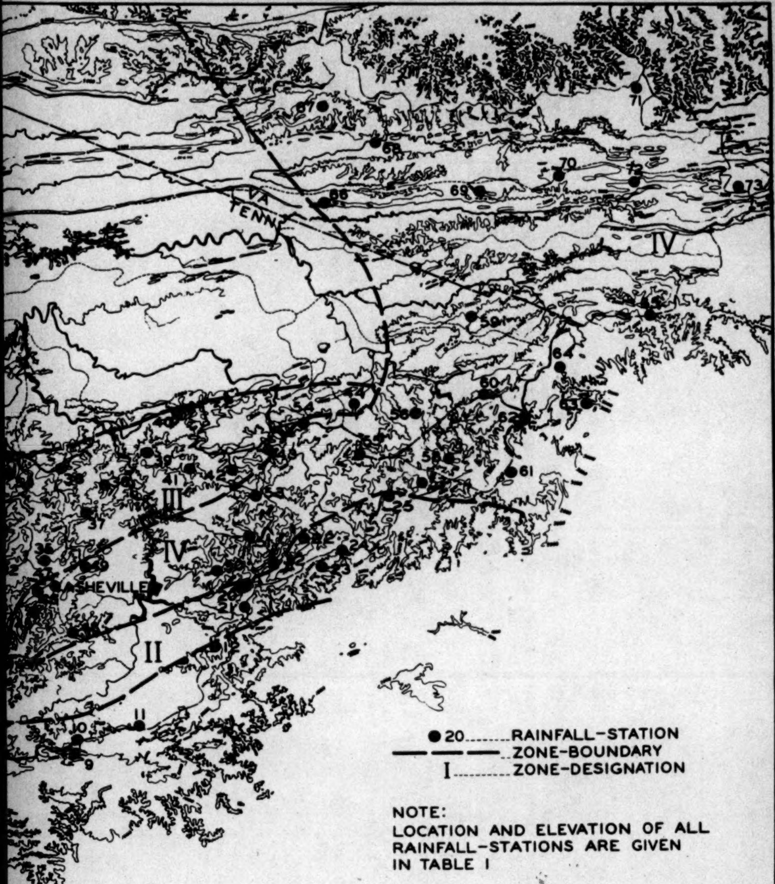


FIG. I—LOCATION OF RAINFALL-STATIONS AND ZONES IN THE SOUTHERN APPALACHION REGION

southwest to northeast, but individual ridges often lie at nearly right-angles to the general direction of the chain and have no general direction. This area contains the highest mountains in the United States east of the Rocky Mountains and is generally known as the Southern Appalachian Region. The Appalachian Mountain chain extends northward across Virginia, Maryland, Pennsylvania, and New York into New England; but, with the exception of a few isolated peaks, its general elevation becomes much lower after it crosses the North Carolina-Virginia State line. This Southern Appalachian Region is shown on Figure 1. About 750 square miles of this southern region have elevations of 4000 to 5000 feet and 170 square miles are over 5000 feet, while a number of individual peaks extend well above 6000 feet.

The eastern range of these mountains, known as the Blue Ridge, forms the general divide


VA
TENN
ASHEVILLE
II
III
IV
IV
● 20 ........ RAINFALL-STATION
— — — .. ZONE-BOUNDARY
I ......... ZONE-DESIGNATION
NOTE:
LOCATION AND ELEVATION OF ALL RAINFALL-STATIONS ARE GIVEN IN TABLE I

between the Atlantic coastal drainage and that of the great Mississippi River Valley, while the southern end of this Southern Appalachian Region, in northern Alabama and Georgia, forms the northern limit of the East Gulf Coast Drainage. Rivers rising in this region flow eastward into the Atlantic Ocean, southward into the Gulf of Mexico, and northward or westward to join the Ohio and Mississippi rivers. Thus it will be seen that the Southern Appalachian Region comprises the principal watershed-divide east of the Continental Divide and is the source of some of the largest rivers in eastern United States. The rainfall over it, therefore, is an important factor to most of the southeastern States.

Sources of moisture--This Southern Appalachian Region is so located that its rainfall is derived from three general sources of moisture. The first and most general of these is the cy-

Table 1--Rainfall-station data, Southern Appalachian Region

| Station No. | TVA No. | Name | State | Elevation above mean sea-level | Latitude | Longitude | Date established | Owner | Type gage | Three-year average |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | feet | ° ' " | ° ' " | | | | inches |
| | | | | | Zone I | | | | | |
| 1 | 109 | Flat Top | Georgia | 3650 | 34 51 28 | 84 30 15 | Dec. 10, 1934 | TVA | Record | 86.70 |
| 2 | 115 | Suches | Georgia | 2800 | 34 41 00 | 84 01 05 | Oct. 30, 1934 | TVA | Can | 80.22 |
| 3 | 140 | Hyatt Creek | North Carolina | 2500 | 35 12 20 | 83 56 37 | Sep. 28, 1934 | TVA | Can | 77.39 |
| 4 | 135 | Neel Gap | Georgia | 3300 | 34 44 03 | 83 54 53 | Dec. 4, 1934 | TVA | Record | 78.78 |
| 5 | 147 | Brasstown Bald | Georgia | 4780 | 34 52 27 | 83 48 40 | Dec. 5, 1934 | TVA | Record | 69.50 |
| 6 | 154 | Tray Mountain | Georgia | 3900 | 34 47 57 | 83 41 28 | Dec. 5, 1934 | TVA | Record | 75.90 |
| 7 | 200 | Coweeta No. 1 | North Carolina | 2875 | 35 04 03 | 83 26 31 | Oct. 18, 1934 | USFS | Record | 74.28 |
| 8 | 201 | Highlands | North Carolina | 3350 | 35 01 45 | 83 11 40 | 1886 | USWB | Can | 80.64 |
| 9 | 284 | Caesars Head | South Carolina | 3115 | 35 05 24 | 82 37 01 | 1925 | USWB | Can | 83.74 |
| 10 | 283 | Cedar Mountain | North Carolina | 2760 | 35 09 03 | 82 38 14 | Sep. 27, 1935 | TVA | Can | 81.20 |
| 11 | 280 | Rush Mountain | North Carolina | 2900 | 35 14 12 | 82 28 15 | Oct. 19, 1934 | TVA | Can | 70.79 |
| 12 | 277 | Garren Creek | North Carolina | 2600 | 35 31 01 | 82 20 21 | Sep. 25, 1935 | TVA | Can | 60.66 |
| | | | | | Zone II | | | | | |
| 13 | 101 | Sassafras Knob | Tennessee | 3300 | 35 05 41 | 84 25 12 | Dec. 6, 1934 | TVA | Record | 61.57 |
| 14 | 179 | Haw Knob | North Carolina | 4980 | 35 18 32 | 84 02 21 | June 28, 1935 | TVA | Record | 86.42 |
| 15 | 142 | Tatham Gap | North Carolina | 3690 | 35 15 08 | 83 48 34 | Nov. 29, 1934 | TVA | Record | 70.88 |
| 16 | 148 | Old Road Gap | North Carolina | 3800 | 35 10 17 | 83 43 51 | Nov. 30, 1934 | TVA | Record | 74.97 |
| 17 | 152 | Glade Gap | North Carolina | 3800 | 35 04 00 | 83 37 52 | Dec. 7, 1934 | TVA | Record | 69.46 |
| 18 | 192 | Erastus | North Carolina | 3500 | 35 11 02 | 83 10 53 | Apr. 1, 1935 | TVA | Can | 65.81 |
| 19 | 191 | Owens Gap | North Carolina | 4100 | 35 11 55 | 82 58 27 | Nov. 2, 1934 | TVA | Can | 74.67 |
| 20 | 271 | North Fork | North Carolina | 2950 | 35 41 27 | 82 19 37 | 1927 | City of Asheville | Record | 59.51 |
| 21 | 272 | Montreat | North Carolina | 2600 | 35 38 51 | 82 18 00 | 1918 | USWB | Can | 57.33 |
| 22 | 232 | Celo | North Carolina | 2800 | 35 52 10 | 82 12 24 | Nov. 12, 1934 | TVA | Can | 54.49 |
| 23 | 234 | Snow Creek | North Carolina | 2600 | 35 57 45 | 82 08 31 | Oct. 23, 1934 | TVA | Can | 47.01 |
| 24 | 235 | Little Switzerland | North Carolina | 3500 | 35 50 58 | 82 05 32 | Oct. 24, 1934 | TVA | Can | 61.83 |
| 25 | 237 | Plumtree | North Carolina | 2900 | 36 01 45 | 82 00 18 | July 1, 1935 | TVA | Can | 56.02 |
| | | | | | Zone III | | | | | |
| 26 | 197 | Wayah Bald | North Carolina | 5330 | 35 10 49 | 83 33 38 | May 8, 1935 | TVA | Record | 73.63 |
| 27 | 184 | Clingmans Dome | North Carolina | 6400 | 35 33 31 | 83 29 43 | Sep. 26, 1935 | TVA | Record | 87.98 |
| 28 | 195 | Raven Mountain | North Carolina | 4500 | 35 19 43 | 83 22 23 | May 23, 1935 | TVA | Record | 64.02 |
| 29 | 210 | Mount LeConte | Tennessee | 6350 | 35 39 12 | 83 26 30 | Apr. 25, 1935 | TVA | Can | 80.24 |
| 30 | 188 | Dicks Creek | North Carolina | 3150 | 35 25 20 | 83 15 15 | Apr. 1, 1935 | TVA | Can | 58.15 |
| 31 | 187 | Spruce Mountain | North Carolina | 4800 | 35 36 34 | 83 11 13 | Dec. 8, 1934 | TVA | Record | 66.09 |
| 32 | 248 | Eaglenest Mountain | North Carolina | 3500 | 35 29 09 | 83 02 26 | Oct. 17, 1935 | TVA | Can | 62.47 |
| 33 | 190 | Haywood Gap | North Carolina | 5250 | 35 18 49 | 82 57 13 | Dec. 7, 1934 | TVA | Record | 69.90 |

clonic disturbances which originate west of the Mississippi River or along the Gulf Coast. These travel in a general northeasterly direction until they pass out to sea, usually in the vicinity of the St. Lawrence River. They produce most of the precipitation in the Mississippi and Ohio valleys and a large percentage of it along the Gulf and South Atlantic coasts.

The second source is the West Indian hurricanes [3], which generally are formed either in

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Zone III--Concluded | | | | | | |
| 34 | 245 | Mount Sterling | North Carolina | 2950 | 35 43 29 | 83 05 22 | Oct. 31, 1934 | TVA | Can | 60.23 |
| 35 | 250 | Chambers Mountain | North Carolina | 4300 | 35 34 04 | 82 54 26 | Nov. 13, 1934 | TVA | Record | 44.10 |
| 36 | 257 | Max Patch Mountain | North Carolina | 4250 | 35 47 40 | 82 57 45 | Oct. 17, 1934 | TVA | Can | 63.46 |
| 37 | 261 | Doggett Gap | North Carolina | 3800 | 35 43 02 | 82 50 19 | Nov. 5, 1934 | TVA | Can | 56.89 |
| 38 | 260 | Big Pine | North Carolina | 2700 | 35 47 17 | 82 49 16 | Oct. 17, 1934 | TVA | Can | 48.25 |
| 39 | 258 | Lonesome Mountain | North Carolina | 2700 | 35 54 38 | 82 44 37 | Oct. 27, 1934 | TVA | Can | 46.66 |
| 40 | 218 | Camp Creek Bald | Tennessee | 4550 | 36 01 46 | 82 42 46 | Dec. 22, 1934 | TVA | Record | 64.29 |
| 41 | 259 | Cody Store | North Carolina | 2500 | 35 54 21 | 82 36 24 | Aug. 3, 1935 | TVA | Can | 48.85 |
| 42 | 227 | McKinney Gap | North Carolina | 4500 | 35 56 48 | 82 28 10 | Oct. 22, 1934 | TVA | Can | 63.51 |
| 43 | 223a | Flat Top Mountain | North Carolina | 2900 | 36 02 01 | 82 23 47 | Jan. 30, 1935 | TVA | Can | 56.35 |
| 44 | 225 | Stone Mountain | Tennessee | 2600 | 36 12 05 | 82 14 22 | Oct. 26, 1934 | TVA | Can | 60.64 |
| | | | | Zone IV | | | | | | |
| 45 | 253 | Dix Creek | North Carolina | 3500 | 35 26 01 | 82 52 33 | Oct. 30, 1934 | TVA | Can | 52.82 |
| 46 | 247 | Waynesville | North Carolina | 2756 | 35 29 00 | 82 59 00 | 1899 | USWB | Can | 50.59 |
| 47 | 251 | Canton | North Carolina | 2600 | 35 31 22 | 82 50 42 | 1930 | USWB | Can | 44.31 |
| 48 | 254 | Mount Pisgah | North Carolina | 5300 | 35 25 29 | 82 44 55 | Dec. 11, 1934 | TVA | Record | 59.56 |
| 49 | 266 | Rockyface Mountain | North Carolina | 3400 | 35 35 07 | 82 47 36 | Oct. 29, 1934 | TVA | Can | 41.74 |
| 50 | 269 | Beetree Gap | North Carolina | 4900 | 35 41 57 | 82 23 55 | Dec. 22, 1934 | City of Asheville | Record | 59.27 |
| 51 | 228 | Coxcomb Mountain | North Carolina | 4250 | 35 48 46 | 82 21 13 | Dec. 17, 1935 | TVA | Record | 49.68 |
| 52 | 233 | Mount Mitchell | North Carolina | 6684 | 35 45 52 | 82 15 55 | 1925 | USWB | Can | 67.88 |
| 53 | 226 | Cane River | North Carolina | 2500 | 35 54 44 | 82 23 29 | Oct. 20, 1934 | TVA | Can | 46.41 |
| 54 | 224 | Beauty Spot | Tennessee | 4400 | 36 07 00 | 82 20 11 | Dec. 19, 1934 | TVA | Record | 52.42 |
| 55 | 231 | Roan High Knob | Tenn.-N.C. | 6100 | 36 06 16 | 82 07 52 | Jan. 3, 1935 | TVA | Record | 59.34 |
| 56 | 298 | Odomville | Tennessee | 2800 | 36 15 21 | 82 00 22 | May 8, 1935 | TVA | Can | 49.84 |
| 57 | 238 | Smoky Gap | North Carolina | 3670 | 36 07 09 | 81 56 07 | Oct. 26, 1934 | TVA | Can | 48.49 |
| 58 | 299 | Banners Elk | North Carolina | 3550 | 36 09 42 | 81 52 55 | 1908 | USWB | Can | 57.48 |
| 59 | 308 | Crandull | Tennessee | 3300 | 36 32 27 | 81 56 37 | May 6, 1935 | TVA | Can | 57.49 |
| 60 | 300 | Reese | North Carolina | 3500 | 36 20 13 | 81 50 11 | May 7, 1935 | TVA | Can | 49.34 |
| 61 | 303 | Boone | North Carolina | 3332 | 36 13 03 | 81 41 04 | 1929 | USWB | Can | 55.07 |
| 62 | 302 | Snake Mountain | North Carolina | 5575 | 36 19 46 | 81 42 28 | June 26, 1935 | TVA | Record | 37.82 |
| 63 | 305 | Jefferson | North Carolina | 2900 | 36 25 00 | 81 29 00 | 1908 | USWB | Can | 50.42 |
| 64 | 304 | Parker | North Carolina | 4075 | 36 30 00 | 81 40 00 | 1918 | USWB | Can | 52.38 |
| 65 | 311 | Troutdale | Virginia | 3450 | 36 59 39 | 81 39 05 | May 17, 1935 | TVA | Can | 53.27 |
| 66 | 314 | Big Knob | Virginia | 3200 | 36 39 52 | 82 30 22 | Feb. 11, 1935 | TVA | Record | 45.71 |
| 67 | 344 | High Knob | Virginia | 4000 | 36 53 10 | 82 37 19 | Feb. 25, 1935 | TVA | Can | 56.94 |
| 68 | 349 | Dungannon | Virginia | 2500 | 36 50 10 | 82 25 56 | May 28, 1935 | TVA | Can | 49.39 |
| 69 | 316 | Holston | Virginia | 3450 | 36 49 36 | 82 05 21 | Apr. 9, 1935 | TVA | Can | 48.54 |
| 70 | 354 | Mutters Gap | Virginia | 3925 | 36 56 51 | 81 52 19 | June 21, 1935 | TVA | Can | 52.99 |
| 71 | 356 | Jewell Ridge | Virginia | 2700 | 37 11 25 | 81 46 48 | Feb. 18, 1935 | TVA | Can | 49.57 |
| 72 | 355 | Spring Creek | Virginia | 3150 | 35 59 39 | 81 39 05 | Feb. 19, 1935 | TVA | Record | 40.60 |
| 73 | 320 | Burkes Garden | Virginia | 3250 | 37 05 20 | 81 20 02 | 1895 | USWB | Can | 50.19 |

the region of the Cape Verde Islands or in the Caribbean Sea near the West Indies. They travel along recurving paths toward the north or west, and many of them strike the Gulf or the South Atlantic coasts with resulting high precipitation over rather wide areas in or near the Southern Appalachian Region. Others pass northward along the Atlantic Coast, but the precipitation accompanying them extends westward over the eastern section of this region. Such disturbances are usually accompanied by very heavy rainfall lasting from two to three days. The occurrence of this type of storm is limited to the period from about May 1 to November 1 of each year.

The third source of precipitation is a rather elusive one. High temperatures prevail over the shallow water of the Gulf of Mexico and over the southern coast of the United States during the summer and produce a high rate of evaporation from these areas. This moisture is picked up by the rising currents of warm air and moved slowly northward in the form of clouds toward the Southern Appalachian Region. These clouds pass over the lowland area south of this region at relatively low elevations and continue to absorb more and more moisture as it is evaporated from the land under them. By the time these warm currents of air reach the vicinity of the Southern Appalachians, they are in a nearly saturated condition. Abruptly, the ground-elevation in the vicinity of the southeastern edge of the Tennessee River Basin change from an average of about 500 feet to about 3000 feet above mean sea-level. This sudden change in elevation produces sharp updrafts of air which act much like the air-currents inside a chimney. These currents rush upward along the general face of the mountains in this vicinity and carry along with them the mass of warm air that is heavily laden with moisture from the Gulf.

When this warm, saturated air rises to elevations of 3000 to 10,000 feet, it encounters much colder strata of air. The temperature of the incoming air is suddenly lowered and its capacity for holding moisture is greatly reduced. The large amount of moisture it carries can no longer be retained and heavy rainfall ensues. This produces almost daily rainfall during the summer at a number of stations in the Southern Appalachian Region and increases very materially the yearly rainfall over this area.

Rainfall-records--United States Weather Bureau stations: Rainfall-stations were operated in the Southern Appalachian Region by cooperative observers under the direction of the Smithsonian Institution and the United States Signal Service from about 1853 until the establishment of the United States Weather Bureau in 1891. Most of these early stations have been continued by the United States Weather Bureau, and a large number of new stations have been established and operated by this agency since that time. All but one of these are cooperative stations and are equipped with the standard United States Weather Bureau can-gages. This equipment is furnished by the Weather Bureau, and the observers receive no pay for their services but compile the records as a hobby or because of their interest in meteorological phenomena.

The Southern Appalachian Region, like most other mountain areas, has always been sparsely inhabited, and the population is largely concentrated in a few medium-sized towns and villages, practically all of which are located in the stream-valleys and at low elevations. There were no good roads into this area prior to about 1925, and large portions of it were practically inaccessible. Few, if any, suitable observers lived at points having high elevations, due to the general inaccessibility of such locations. Prior to the establishment of the Tennessee Valley Authority, in 1933, there were only 13 rainfall-stations in this whole area with elevations above 2500 feet, and only two of these--Parker and Mount Mitchell--were at elevations of over 4000 feet. This accounts for the general lack of rainfall-data for high elevations in the Southern Appalachian Region.

Tennessee Valley Authority stations: An investigation was made by the Tennessee Valley Authority in 1934 of all the available rainfall-data for this area. This study showed conclusively that additional rainfall-records were needed, particularly at high elevations, before a complete study of the water-resources of the region could be made. A number of good roads had been built through the region between 1925 and 1934, and points with high elevations were much more accessible than before. Automatic rain-gages had passed the experimental stage and were now standard rainfall-equipment. Between 1934 and 1936, 37 automatic gages were purchased by the Tennessee Valley Authority and installed at suitable locations in the Tennessee River Basin above Chattanooga. About 128 can-gages were also installed in this area to supplement the stations operated by the United States Weather Bureau and the new automatic stations established by the Tennessee Valley Authority.

The topography of the area, location of existing Weather Bureau stations, direction of storms, and other pertinent features of the area were carefully studied before any of these gages were installed, and the new stations were located so as to make the coverage over the entire area as complete as possible.

Miscellaneous stations: A few additional stations are operated by the United States Forest Service, the city of Asheville, the Aluminum Company of America, and by private individuals. Records for these showed that all but two of them were at relatively low elevations and that they were of minor importance in this study.

Selection of records for study--All of the rainfall-records available were carefully examined to determine their continuity and length, the geographical location of station, its elevation above mean sea-level, and its normal rainfall.

This preliminary study showed that there was practically no relation between elevation and the amount of rainfall at stations having elevations below 2500 feet. Therefore, for this investigation, only those stations located at 2500 feet or over were used, and the pertinent data for these stations are shown in Table 1. About 20 stations below 2500 feet were also studied as an auxiliary aid in fixing the lower limits of the curves shown, but data for these stations have been omitted in this report.

It was found that 84 stations in this region were located above this elevation but that a complete record of monthly rainfall for the three-year period, October 1, 1935, to September 30, 1938, was available only for 73 of them. These 73 stations were selected for study, and their locations are shown on Figure 1, while their elevations and other characteristics are given in Table 1. Reference to this Table shows that the elevations of these 73 stations ranged from 2500 to 6684 feet and that they were distributed as follows in the several 500-foot ranges:

| Range in feet | Number of stations USWB | TVA | Other | Total number | Percentage of total number |
|---|---|---|---|---|---|
| 2500 to 3000 | 4 | 18 | 2 | 24 | 33 |
| 3000 to 3500 | 4 | 9 | 0 | 13 | 18 |
| 3500 to 4000 | 1 | 13 | 0 | 14 | 19 |
| 4000 to 4500 | 1 | 6 | 0 | 8 | 11 |
| 4500 to 5000 | 0 | 5 | 1 | 6 | 8 |
| 5000 to 5500 | 0 | 4 | 0 | 3 | 4 |
| 5500 to 6000 | 0 | 1 | 0 | 1 | 1 |
| Above 6000 | 1 | 3 | 0 | 4 | 6 |

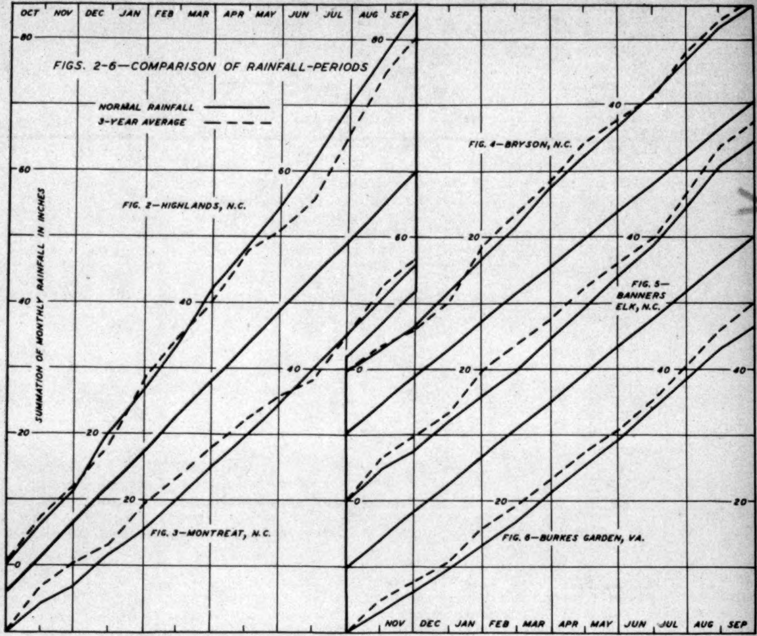
Average annual rainfall--The rainfall recorded in each month, during the three-year period, at each of the 73 stations, was carefully tabulated and a monthly average was obtained for each of these stations. These monthly averages were summed up to obtain the yearly average. All of these yearly averages are shown in Table 1. These values range from 37.82 inches at Snake Mountain to 87.98 inches at Clingman's.

Comparison of records--Four of the 11 United States Weather Bureau stations, located above 2500 feet in the area, were found to have continuous records of 20 years or longer. These records, together with those at the United States Weather Bureau station located at Bryson, North Carolina, were used to compare the average annual rainfall as determined from the three-year period of 1935-38 with the normal rainfall for the area as determined from the longer records. Mass-curves of the normal monthly rainfall for the long periods and the average monthly rainfall for the three-year period are shown on Figures 2 to 6. A summation of these data is as follows:

| Station | Elevation in feet | Length of record | Normal yearly rainfall | Three-year average rainfall | Percentage-variation from normal |
|---|---|---|---|---|---|
| Highlands | 3350 | 51 years | 84.90 | 80.74 | -5.0 |
| Montreat | 2600 | 21 years | 56.00 | 57.03 | +1.8 |
| Bryson | 1800 | 49 years | 54.81 | 56.01 | +2.2 |
| Banners Elk | 3550 | 30 years | 55.13 | 57.48 | +4.3 |
| Burkes Garden | 3250 | 43 years | 46.47 | 50.19 | +8.0 |

This tabulation shows that the average annual rainfall for the three-year period of October 1, 1935, to September 30, 1938, represents a very close approximation of the long-term normal rainfall for these stations. Since locations of the stations selected for comparison are such that their records are fiarly indicative of the normal rainfall over the entire area, it is believed that the three-year period investigated at the 73 stations is also reasonably representative of the normal rainfall that may be expected over a long-term period at these stations.

Grouping of stations--Early attempts to determine a rainfall-elevation relationship ended in failure due to the assumption that all the stations belonged in a single rainfall-group. Later, when topography of the area, direction of moisture-travel, and location of principal mountain ridges were taken into account, it was found that with only five exceptions the 73 stations fell into four natural groups or zones. These zones have been designated by Roman numerals I to IV inclusive and are shown on Figure 1. The five exceptions to this grouping are as follows:



FIGS. 2-6—COMPARISON OF RAINFALL-PERIODS

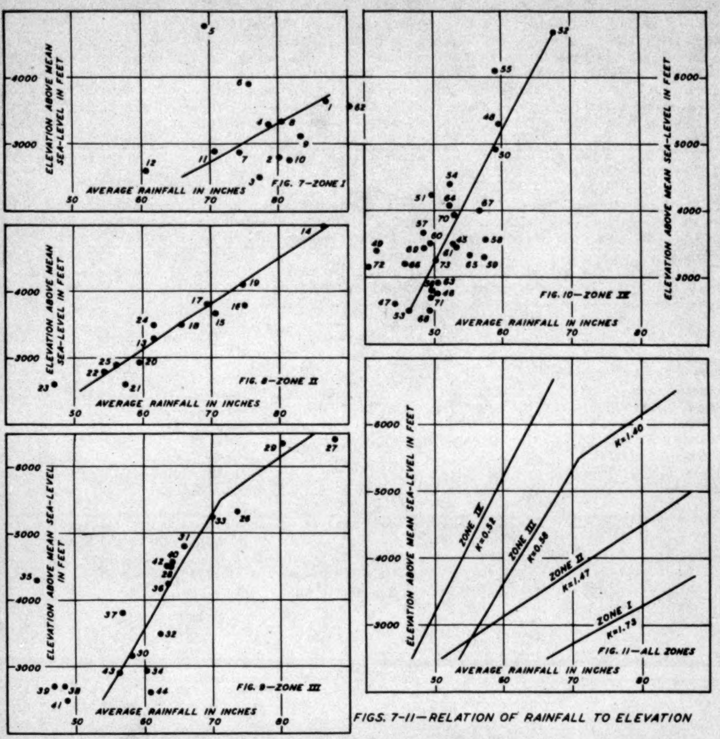
| Station | Zone | Elevation | Average rainfall |
|---|---|---|---|
| Brasstown Bald | I | 4780 | 69.50 |
| Rockyface Mountain | IV | 3400 | 41.74 |
| Chambers Mountain | III | 4300 | 44.10 |
| Snake Mountain | IV | 5575 | 37.82 |
| Spring Creek | IV | 3150 | 40.60 |

Further investigation of these five stations indicates that they are so located as to be shielded from the full effect of the rainfall that occurs over their particular zones. Their records, therefore, are not representative of rainfall-conditions in the zones but only over small areas immediately adjacent to the stations.

Rainfall-elevation curves--The three-year average rainfall that occurred at each of the stations in the above zones was plotted as abscissa with the elevation of the station as ordinate, and a curve was drawn through the mean of the points in each zone. These curves are shown on Figures 7 to 10, along with the points upon which they are based. It will be noted that the points do not all fall exactly on the curves, but this is to be expected since the stations in each zone are rather widely scattered. Likewise, the elevations of most of these stations have been determined by approximate methods and not by actual surveys and may be subject to errors of considerable magnitude. A check of the points lying farthest away from the curves also shows that most of these points are for stations equipped with can-gages.

The straight-line equation developed by J. B. Lippincott [1] in 1899 was found to apply to these curves. This equation is

$$R' = R + K(A/100)$$



FIGS. 7-11—RELATION OF RAINFALL TO ELEVATION

in which R' and R are the average annual rainfalls in inches at the higher and lower points, respectively, A is the difference in altitude in feet, and K is a constant for each zone. The following values were obtained for K by use of this equation:

| Zone | Range in elevation in feet above mean sea-level | K |
|---|---|---|
| I | 2500 to 3800 | 1.73 |
| II | 2500 to 5000 | 1.47 |
| III | 2500 to 5500 | 0.58 |
| III | 5500 to 6500 | 1.40 |
| IV | 2500 to 6700 | 0.52 |

The above values for K are all very much higher than those obtained by Dr. Mead [2] in 1919 for stations in western United States, but it is believed that they should be, on account of the much higher rainfall over this Southern Appalachian Region than over that investigated by Dr. Mead. It should be noted that the highest value of K and, consequently, the greatest amount of rainfall, occurs over zone I, and that the values of K decrease toward the northeast. It is believed that this is a logical decrease since the principal direction of moisture-travel is from the south or southwest toward the north or northeast and that more and more moisture is precipitated as the higher elevations are encountered. This is borne out, particularly by the stations in zone III. The stations below 5500 feet in this zone are somewhat shielded by the high elevations in zones I and II, and their average annual rainfall is correspondingly less than that for stations of the same elevation in these two zones. This zone, however, covers the highest part of the Great Smoky Mountains, and there are two stations in operation above 6300 feet. Averages at these two stations show that they possess much the same characteristics as those stations in zone II, and the curve for zone III has been broken at the 5500-foot level and drawn above this elevation so that it is practically parallel to the curve for zone II. It has a value of K for the section above this level only slightly less than that for zone II.

The four curves derived for the different zones are shown on Figure 11 along with the values of K derived for each of them.

Other stations--There are 11 additional stations located in the Southern Appalachian Region at elevations ranging from 2500 to 3300 feet, but their records are incomplete for the three-year period investigated, and they have been omitted from this study.

United States Weather Bureau records list eight additional stations located above 3000 feet, in Virginia and West Virginia, but north of the Southern Appalachian Region. Similar data have been computed for these stations and are as follows:

| Name | State | Elevation above mean sea-level | Owner | Gage-type | Three-year average (1935-1938) |
|---|---|---|---|---|---|
| Circleville (Spruce Knob) | West Virginia | 4550 | USWB | Can | 52.22 |
| Mountain Lake | Virginia | 4000 | USWB | Can | Short record |
| Big Meadows | Virginia | 3500 | USWB | Can | 55.11 |
| Shenandoah Camp 3 | Virginia | 3300 | USWB | Can | 54.38 |
| Sexton Shelter | Virginia | 3300 | USWB | Can | 49.89 |
| Stony River Dam | West Virginia | 3300 | USWB | Can | 42.95 |
| Davis | West Virginia | 3093 | USWB | Can | 59.10 |
| Monterey | Virginia | 3008 | USWB | Can | 48.06 |

The average rainfall recorded at the above stations indicates that, with the exception of the station at Davis, West Virginia, they all possess the characteristics of zone IV, and their points when plotted fall reasonably close to the curve as determined for that zone. Rainfall at the Davis station may be influenced much more than that at the other stations by the proximity of this station to the principal path of low-pressure areas passing over the main Ohio River Basin.

Conclusions--Study of the rainfall-records of 73 stations located in the Southern Appalachian Region and at elevations ranging from 2500 to about 6700 feet indicates that:

(1) The Southern Appalachian Region may be subdivided into four rainfall-zones whose boundaries are dependent upon the principal direction of moisture-travel and the topography of the area.

(2) A definite relation exists between the rainfall and elevations peculiar to each of these zones which can be expressed by a straight-line equation of the type $R' = R + K (A/100)$ as proposed by Lippincott [1] for western areas in 1899.

(3) The coefficient K in the above equation varies for each zone and generally decreases in the principal direction of moisture-travel.

(4) The average annual rainfall as computed from the three-year period of October 1, 1935, to September 30, 1938, was approximately equal to the normal annual rainfall for the area, and therefore this short period appears to be representative of the normal rainfall to be expected over the area.

(5) Longer records and a better determination of the elevation at most of the stations are desirable, and it is expected that such data will result in the points in each zone falling closer to the curves shown for these zones.

These results are not intended to be conclusive or final, due to the short records on which they are based, but they are believed to be indicative of the relation between rainfall and elevation which exists in this Southern Appalachian Region. It is hoped that they may form the basis for more extensive studies in the future when longer records become available.

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## THE STRUCTURE OF DISCHARGE-RECESSION CURVES

Bertram S. Barnes

*Synopsis*--Storm-discharge of streams in the upper Mississippi Valley consists of surface-flow and storm-seepage. The total runoff, resulting from a storm, of either of these components does not bear a fixed relation to the runoff of the other. The two are influenced by different sets of conditions.

The two components of the storm-flow can be separated by graphical analysis. A reversal of the process has been found useful in determining the hydrograph of ground-water flow.

*Sources of stream-flow*--Hydrographs of streams in the upper Mississippi Valley ordinarily reflect the characteristics of flow from three different sources, described as follows:

(1) Surface-flow--This results from rain or melted snow which has entered the stream-sources by a surface-route, without having penetrated the surface of the soil. It produces a hydrograph whose form is determined largely by the duration of the storm or thaw and the variations in its intensity, and by the channel-storage characteristics of the system.

(2) Storm-seepage--This consists of water which has penetrated only the upper soil-layers during a rainstorm or a thaw and has filtered more or less horizontally through the soil to discharge into the stream-system by seepage. It was observed by the writer in 1936 while analyzing discharge records of Zumbro River in Minnesota and called by him "secondary base-flow." The same phenomenon has been observed by Dr. W. C. Lowdermilk [see 1 of "References" at end of paper] and by C. R. Hursh [2], and given the name of "storm-seepage." The latter term will be used in this paper. The hydrograph of an event of storm-seepage is characterized by a fairly rapid rise and a flattened peak, the latter usually occurring from two to three days after the peak of surface-flow. The recession is much more gradual than that of surface-flow. On account of its longer time-base its shape is not greatly influenced by channel-storage or by the duration of the storm, and depends more upon the soil-characteristics of the region.

(3) Base-flow--This is the discharge into the stream-system from storage in the ground at or below the ground-water level. The hydrograph of base-flow may sometimes exhibit rather sharp rises but there is always a very conspicuous time-lag between the storm and the rise. The recession of an event of base-flow is very gradual except, of course, when the discharge is impeded temporarily by the rapid formation of ice in the headwaters of the stream-system or is otherwise regulated.

The storm-flow consists of the first two of the foregoing components, namely, surface-flow and storm-seepage. The basins of the upper Mississippi Valley discharge such a small fraction of the total precipitation in the form of surface-flow that variations in the momentary intensity of the rainfall and daily changes in the infiltration-capacity of the surface-soil influence the amount of surface-runoff very greatly. To express this thought in a different way: A decrease of a relatively small percentage in the amount of water which enters the ground can easily double the amount of water which does not enter. The total amount of storm-seepage, however, seems to be affected very little by the momentary rainfall-intensities of the storm. It appears to be more largely influenced by the total amount of rainfall and its duration. We find, therefore, that although a satisfactory unit-graph can be made for either of the two components of the storm-flow, the areas under the hydrographs of the two components resulting from any given storm do not bear a fixed relation to each other. It is believed that this fact will be found to be significant in connection with index-basin studies, since the total storm-discharge from an index-basin may not be at all comparable under different storm-conditions to the total storm-discharge from a larger basin.

*Form of the recession-curve*--Horner and Flynt [3] found that the recession from an event of surface-flow can be expressed by the equation

$$Q_d = Q_m/k^{(t-t_\ell)}$$

where $Q_d$ is the discharge at a time-interval t after the hour of the rainfall, $Q_m$ is the peak-discharge, and $t_\ell$ is the lag in time from the rainfall to the peak-discharge. In the experiments from which the above equation was derived storm-discharge was measured in a city sewer from which all base-flow and storm-seepage were presumably excluded. Studies made in the office of the writer indicate that the same form of equation is applicable to the recession of an event of storm-seepage. The equation adopted in 1936 by the writer is

$$Q_t = Q_0 k^t \tag{2}$$

where Q and Q are values of the discharge at any two instants separated by the time-interval t, and k is a constant known as the "depletion-factor." It is apparent that equations (1) and (2) are merely different expressions of the same relationship.

Equations (1) and (2) appear to be applicable also to the recession of base-flow during periods when no recharge to ground-water is taking place. The recessions of the three components of flow are therefore best studied by plotting them on graph paper having a logarithmic discharge-scale and an ordinary time-scale. As an example of this method of study an analysis of the discharge-record of Iowa River at Marshalltown, Iowa, for the period July 12 to August 16, 1935, is presented in this paper.

Analysis of Marshalltown record--Iowa River Basin has an area above Marshalltown of 1500 square miles and an average width of 16 miles. Above Iowa City it has an area of 3230 square miles and an average width of 18 miles. The main stream has a length of 139 miles from the source to Marshalltown, with a fall of 350 feet, and 120 miles from Marshalltown to Iowa City, with a fall of 210 feet. The length of the Basin above Iowa City is about 180 miles, of which about 90 miles lies above Marshalltown. The river and practically all its tributaries flow in a southeasterly direction. The discharge-record at Marshalltown is slightly affected by the operation of a small power-plant at Iowa Falls and the record at Iowa City is affected by regulation from several plants, the two largest being within three miles of the gage.

During the months of July, August, and September, 1935, there was a steady depletion of ground-water storage in Iowa River Basin with little or no recharge, and several well-separated storms occurred in this period. Hydrographs of the mean daily discharge at Iowa City and Marshalltown, from data published by the United States Geological Survey [4], are shown in Figure 1. The base-flow in each case has been drawn as a straight line, representing constant values of the daily depletion-factor k of 0.980 and 0.983, respectively. The mean daily precipitation-depths above Iowa City and above Marshalltown were obtained from isohyetal maps based on data obtained by the United States Weather Bureau [5], and are plotted below the hydrographs. It is apparent that some rain must have fallen on days when none was reported. Probably these rains were concentrated in small areas lying between the reporting stations. The characteristic double peak in Iowa City which ordinarily results from a single rainstorm has been discussed by the late Professor F. A. Nagler [6].

The storm-flow for the period July 6 to 22 has been obtained by subtracting the base-flow from the mean daily discharge and is plotted on the right-hand side of Figure 1. It was assumed that by July 11 the surface-flow from previous rains had been reduced to a negligible amount and that the recession of storm-flow for the ensuing ten days represented the depletion of the storm-seepage. These recessions are drawn in Figure 1 as straight lines representing constant values of k of 0.711 for Iowa City and 0.694 for Marshalltown.

The establishment of values of k for the base-flow and storm-seepage as described above makes it possible to isolate the events of surface-flow. For this purpose the mean daily values of total discharge were found inadequate because the surface-flow would not attain a constant value of k more than 24 hours before the rise of the storm-seepage became appreciable. It was therefore necessary to obtain instantaneous values of discharge taken at shorter intervals of time.

The original water-stage recorder charts obtained at Marshalltown by the Geological Survey were carefully studied and the basic record was found to be very good. The instrument failed to operate from 7 a.m., July 23, to 10 a.m. of the day following. No fluctuation of the pen occurred from 3:50 p.m., August 7, when the float was depressed by the observer to mark the hour of his visit, until 8 a.m. of the next day. It is believed that the pen-mechanism was stuck during this interval and there is a possible error of 0.01 foot in the gage-height correction for the days immediately proceeding and following the period. The result of our subsequent plotting also suggests that a small rise and fall of the river probably occurred during the few hours in which the pen was stuck. It should be noted here that these errors are far too small to

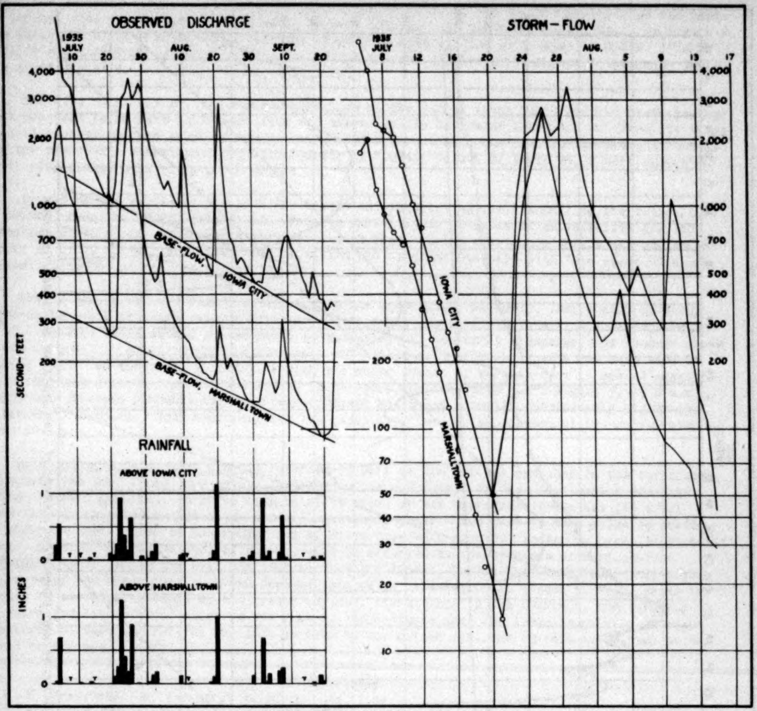

*FIG. 1—DETERMINATION OF 24-HOUR DEPLETION-FACTORS FOR BASE-FLOW AND STORM-SEEPAGE, IOWA RIVER AT MARSHALLTOWN AND IOWA CITY*

affect the accuracy of the published discharge-records of the Geological Survey for the station. They are, however, significant in the present study.

From two to eight values per day of the gage-height were picked off and tabulated. The corresponding instantaneous values of the discharge were determined from a rating curve prepared by the Geological Survey and have been indicated by the small circles in Figure 2. These values were calculated only to three significant figures and in no case closer than one second-foot. Errors from this source may therefore amount to five second-feet for values of total discharge greater than 1000 second-feet and in all cases to a fairly large percentage of error for components of flow amounting to ten second-feet or less. A slight regulation by the power-plant 50 miles above Marshalltown is plainly evident in Figure 2, and the effects of daily evaporation, transpiration, and changing barometric pressure are probably appreciable. The sum of the components of flow calculated as described in the following paragraphs has been taken every six hours and is represented in Figure 2 by the solid line along which the circles lie.

The previously determined value of k, 0.694, was applied from July 12 and the values of the storm-seepage were tabulated for the end of each six-hour period until July 30, when the amounts became less than 0.5 second-foot and were considered to be zero. (Perhaps the values of the storm-seepage for this period should have been taken a little smaller, using the same value of k, so that the reconstructed hydrograph of total discharge would lie along the lower boundary of

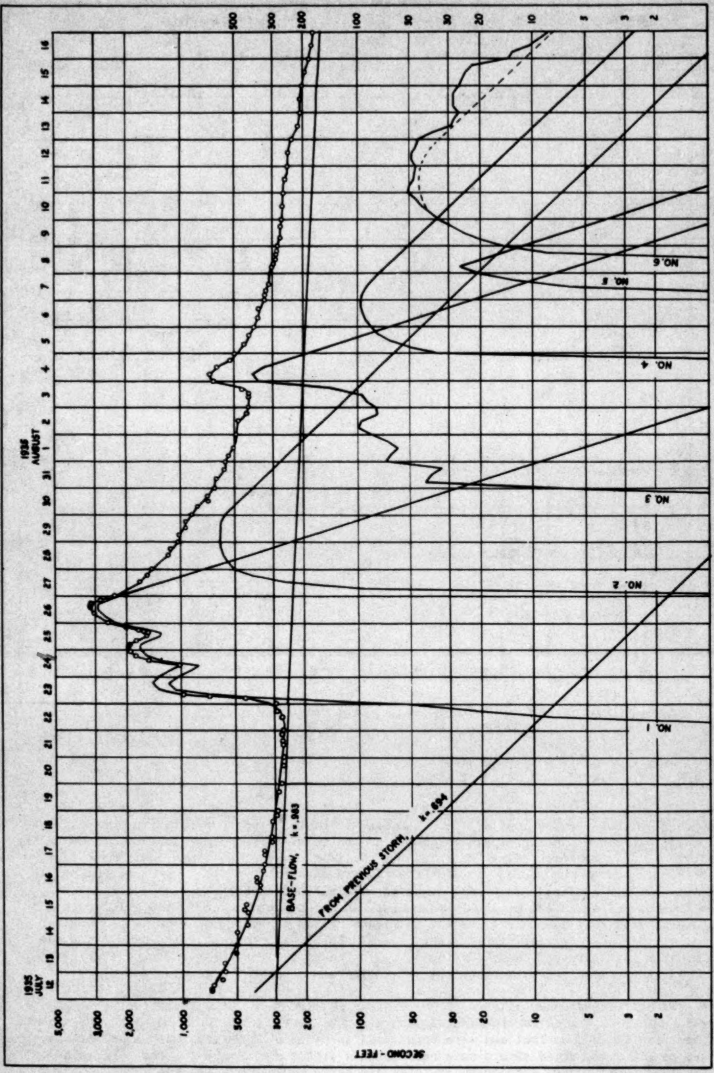

FIG. 2—OBSERVED DISCHARGE AND COMPONENT EVENTS AT IOWA RIVER AT MARSHALLTOWN, IOWA

the group of circled points.) By subtracting these values from the storm-flow the rise and peak of surface-flow for the period July 22 to 26 were obtained and plotted as Event No. 1 in Figure 2. The recession of this event up to midnight of July 26 gave a value of k equal to 0.329. The recession was therefore extended on this same slope and the six-hourly values were tabulated until 6 p.m. of August 3, when they became negligible.

Starting with July 27, the six-hourly values of the sum of Event No. 1 and the storm-seepage from previous rains were subtracted from the storm-flow to determine Event No. 2. From its shape this is clearly another event of storm-seepage and its recession was arbitrarily brought down using the previously established depletion-factor of 0.694. Values of Event No. 2 were tabulated until they became negligible about August 17.

By adding the values of the previous events and subtracting their sums from the storm-flow, as before, Event No. 3 was determined. This is unmistakably an event of surface-flow and its recession up to 6 p.m. of August 4 provides a good check on the previously determined depletion-factor of 0.329 for surface-flow. The recession was extended downward with this value of k and became negligible at noon of August 10.

Events Nos. 4, 5, and 6 were determined in the same manner as above. No. 6 will be recognized as an event of storm-seepage with three very small events of surface-flow superimposed upon it. Because these events are so small in comparison to the total discharge, and because units of one second-foot would not define them with sufficient accuracy, no attempt has been made to isolate them. In comparing Event No. 5 with the other events of surface-flow it should again be noted that the recorder-pen did not appear to be operating from 3:50 p.m., August 7, to 8 a.m., August 8. It seems probable that the peak of Event No. 5 was actually considerably higher than it has been computed. This would explain the peculiarly rounded appearance of the rising limb of Event No. 6.

Determining ground-water flow--A reversal of part of the process outlined in the foregoing paragraphs has been found very useful in defining the hydrograph of base-flow during the late spring, summer, and fall. A trial base is first drawn on the hydrograph-sheet and the trial storm-flow is computed and plotted on semi-logarithmic paper. The base is then adjusted until the mid-portions of most of the recessions of storm-flow, when plotted, appear as parallel straight lines. Some of the recessions, of course, will be affected by the presence of surface-flow throughout their length and will not plot as straight lines. During the winter and early spring the shape of the hydrograph of storm-seepage appears to be affected by frozen subsoil, water impounded in the form of slush on the ground-surface, ice-storage in the channels, and possibly by the increased viscosity of water in the soil at temperatures near the freezing point. Attempts to analyze stream-flow records for such periods by the method outlined in this paper have so far proved rather unsuccessful.

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## A CONCEPTION OF RUNOFF-PHENOMENA

Franklin F. Snyder

Introduction--The problem of transforming observed precipitation into stream-flow for a natural drainage-basin can be divided into two parts. The first part requires a procedure for determining the amount and kind of runoff that occurs under various conditions. The second part is concerned with the shaping of the runoff into a discharge-hydrograph for a particular gaging station. (Rainfall-eccentricities often provide more difficulties than either of the above.)

Considerable investigation has been made and is being continued along both lines of research. The unit-hydrograph and related methods now provide a means of shaping discharge-

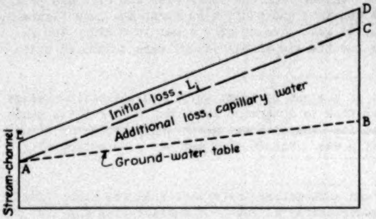

FIG. 1 - SCHEMATIC DIAGRAM OF NATURAL DRAINAGE-BASIN

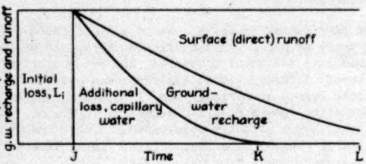
Rate of precipitation, loss g.w. recharge and runoff
Surface (direct) runoff
Initial loss, $L_i$
Additional loss, capillary water
Ground-water recharge
J
Time
K
L

FIG. 2 - SCHEMATIC DIAGRAM OF RAINFALL-RUNOFF RELATIONS

hydrographs as accurately as is required by the practical considerations of most problems. However, it is believed that methods for determining the amount and kind of runoff which occur under various conditions have not been demonstrated to an equivalent refinement. It is with the latter problem that this paper is concerned.

General conception of runoff-phenomena--In analyzing the records of stream-flow and rainfall for a particular drainage-basin, a general conception of rainfall- and runoff-relations is necessary. A number of different ideas prevail, but fundamentally there are no great differences in theory. In most cases, practical considerations determine the manner in which observed data are to be used. The following conception has been used in studies of rainfall-runoff relations for use in flood-forecasting on headwater-basins and is herein refined for additional accuracy. Definitions of the various terms used are given in the appendix.

All natural drainage-basins can be considered to consist of a large number of smaller basins. Each sub-basin has some surface-area with little or no soil-cover while other sections of the same sub-basin have a very thick soil-mantle. Figure 1 is the schematic profile of a sub-area which is considered to be representative of a natural drainage-basin. The basin has been rearranged into a strip of land bordering a drainage-channel on a basis of average depth to the ground-water table (shallow depths nearest the channel). The width of the strip is variable and depends on the relative amounts of surface-area corresponding to the various depths to the ground-water table.

Existing soil-condition or the relative amount of moisture in the soil is considered to be the main factor in determining the volume of runoff for a given rain. The assumption, to be modified later, is now made that ground-water discharge is the best generally available index of soil-moisture. This includes the tacit assumption of fairly constant temperatures or evaporation-and-transpiration opportunity. The use of ground-water discharge as an index of runoff-conditions requires a well-defined procedure for forecasting its occurrence.

It is assumed that for a particular value of ground-water discharge (occurring with the ground-water table in position AB, Fig. 1) there is a value of initial loss which must be satisfied before runoff can occur. This initial loss, $L_1$, is considered to be the amount necessary to wet the vegetation and ground-surface and satisfy the capillary deficiency of the soil-zone ACDE of Figure 1. Figure 2 shows the quantitative division of a rain of constant rate into its various components with J representing the time at which the initial loss has been satisfied. After initial loss is satisfied, the subsequent rainfall is considered to separate into (1) additional loss, or capillary water, (2) ground-water recharge, and (3) surface-runoff or direct runoff.

The additional loss or accretion to capillary water is necessary to bring the soil-zone ABC (Fig. 1) to capillary capacity. This is a gradual process requiring a decreasing quantity of moisture as the lower limit of soil with no capillary deficiency, represented by line AC, Figure 1, (at time J) moves to the right in parallel positions. The water falling near point E provides the initial runoff, part of it becoming gravity-water as it passes through the zone of no capillary deficiency to later join the ground-water zone as ground-water recharge. The remainder of the water falling near point E becomes direct runoff either from the top of the soil-surface or out of the upper soil into the channel.

As more rain occurs and the region of capillary deficiency decreases, the area from which all the rainfall becomes runoff gradually increases, until at time K (Fig. 2) there is very little additional loss and ground-water recharge and surface-runoff account for practically all the rainfall. During this same period, time J to K, a zone of soil filled with gravity-water is

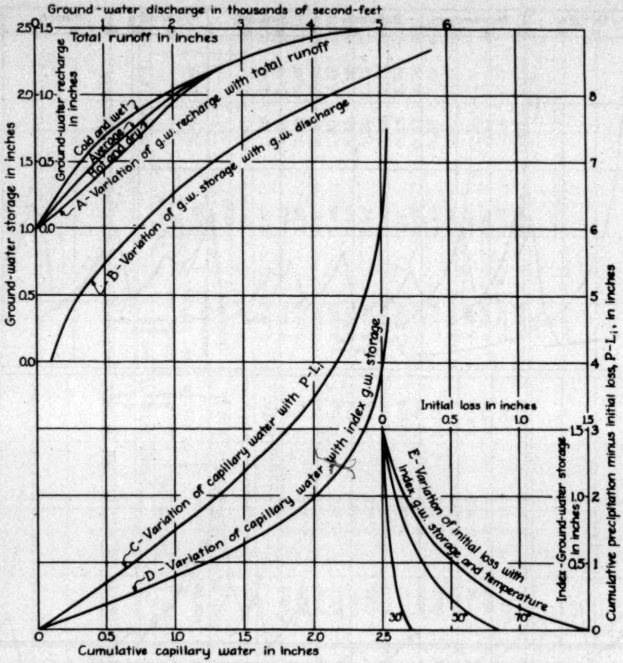

FIG. 3. - HYDROLOGIC CHARACTERISTICS OF SCHUYLKILL RIVER-BASIN ABOVE POTTSTOWN, PA.

developing parallel to surface ED. Part of this gravity-water will eventually reach the ground-water table (that falling near end E). Water falling near end D will first be gravity-water, but, as it penetrates downward, will become capillary water as it enters the zone of capillary deficiency. The penetration of water to satisfy capillary deficiency is more rapid than the penetration of gravity-water. At time L after all the soil has been saturated (filled with gravity-water) all the rainfall occurs as direct runoff except the small amount of water required to maintain ground-water discharge at its maximum.

With the exception of torrential storms on small areas and long drizzling rains, volumetric relations such as those expressed by Figure 2 are assumed to exist regardless of variations in the rate of precipitation.

Example--The Schuylkill River Basin above Pottstown, Pennsylvania, is used as an example in developing the necessary working tools to apply the above conception of runoff. This watershed has a drainage-area of 1147 square miles. While the general procedure can be applied to any stream-flow record in the humid sections of the United States, the detailed methods given herein were developed for use in the Appalachian Highlands. The various steps are discussed under separate headings but they are not entirely independent of each other.

Hydrographs--Hydrographs of mean daily discharge are plotted for the period of record being studied. The time-scale generally used is 10 or 20 days to an inch. A vertical discharge-scale is selected such that the average annual minimum discharge will have an ordinate of not less than one-tenth inch.

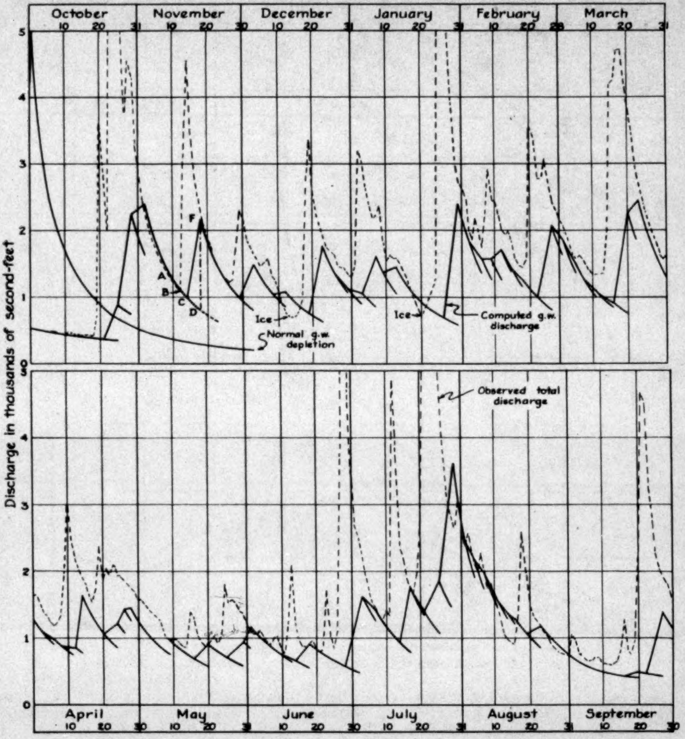

FIG. 4 - COMPUTED GROUND-WATER DISCHARGE FOR SCHUYLKILL RIVER AT POTTSTOWN, PA. (1937-1938)

With the discharge-scale determined on this basis, some of the higher daily values will plot off the chart. This causes little difficulty since the hydrographs are used mainly to study ground-water discharge and the values of the higher flows can be plotted to an auxiliary scale or noted numerically. A logarithmic vertical scale minimizes these difficulties. The kind of paper used is generally determined by personal preference.

Normal ground-water depletion-curve--The normal ground-water depletion-curve is obtained from segments of the hydrographs when there is no surface-runoff in the channels. After a flood-crest, a sufficient number of days is allowed for the flow created by surface-runoff to have passed the gaging station. The succeeding recession is then a ground-water depletion-curve until another storm causes surface-runoff or ground-water recharge.

Usually no one depletion can be found that will cover the entire range of ground-water discharge, so a number of such segments are combined and a normal curve defined. This is readily accomplished by use of a piece of tracing paper having the same horizontal and vertical scales as the hydrographs. The tracing paper is slipped horizontally over the hydrograph-sheet and the various ground-water depletion-segments are traced thereon. These, when combined, produce a normal depletion-curve for the station. Differences in the depletions can be distinguished for summer and winter periods, but a normal curve is usually satisfactory and it can be adjusted as explained later.

Table 1--Ground-water depletion- and storage-curves and initial loss for Schuylkill River above Pottstown, Pennsylvania

| Discharge, second-feet (1) | Time, days from maximum discharge (2) | Increment of time, days (3) | Average discharge, second-feet (4) | Ground-water storage | | | | | Initial loss, inches | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Column (3) | column (4) | Summation of column (6), inches (7) | Correction for current recharge, inches (8) | Adjusted, column (7) plus column (8), inches (9) | 70°F (10) | 50°F (11) | 30°F (12) |
| | | | | Second-foot days (5) | Inches on area (6) | | | | | | |
| 200 | 64.0 | | | | | 0.000 | 0.000 | 0.00 | 1.50 | 0.85 | 0.20 |
| 300 | 47.0 | 17.0 | 250 | 4250 | 0.138 | 0.138 | 0.006 | 0.14 | 1.06 | 0.60 | 0.14 |
| 400 | 38.0 | 9.0 | 350 | 3150 | 0.102 | 0.240 | 0.013 | 0.25 | 0.84 | 0.47 | 0.11 |
| 500 | 32.0 | 6.0 | 450 | 2700 | 0.114 | 0.354 | 0.020 | 0.37 | 0.68 | 0.38 | 0.09 |
| 600 | 27.8 | 4.2 | 550 | 2310 | 0.075 | 0.429 | 0.026 | 0.46 | 0.57 | 0.32 | 0.08 |
| 750 | 23.0 | 4.8 | 675 | 3240 | 0.105 | 0.534 | 0.035 | 0.57 | 0.45 | 0.26 | 0.06 |
| 1000 | 18.0 | 5.0 | 875 | 4380 | 0.142 | 0.676 | 0.052 | 0.73 | 0.32 | 0.18 | 0.04 |
| 1250 | 14.4 | 3.6 | 1125 | 4050 | 0.132 | 0.808 | 0.068 | 0.88 | 0.23 | 0.13 | 0.03 |
| 1500 | 11.7 | 2.7 | 1375 | 3710 | 0.120 | 0.928 | 0.084 | 1.01 | 0.16 | 0.09 | 0.02 |
| 2000 | 8.0 | 3.7 | 1750 | 6470 | 0.210 | 1.138 | 0.117 | 1.26 | 0.07 | 0.04 | 0.01 |
| 2500 | 5.4 | 2.6 | 2250 | 5850 | 0.190 | 1.328 | 0.149 | 1.48 | 0.00 | 0.00 | 0.00 |
| 2950 | 4.0 | 1.4 | 2725 | 3810 | 0.124 | 1.452 | 0.179 | 1.63 | .... | .... | .... |
| 3350 | 3.0 | 1.0 | 3150 | 3150 | 0.102 | 1.554 | 0.204 | 1.76 | .... | .... | .... |
| 3900 | 2.0 | 1.0 | 3625 | 3620 | 0.118 | 1.672 | 0.240 | 1.91 | .... | .... | .... |
| 4700 | 1.0 | 1.0 | 4300 | 4300 | 0.140 | 1.812 | 0.292 | 2.10 | .... | .... | .... |
| 5750 | 0.0 | 1.0 | 5225 | 5220 | 0.170 | 1.982 | 0.360 | 2.34 | .... | .... | .... |

The normal depletion-curve desired is the one that best fits most of the actual cases. For this reason, it is better to arrive at a preliminary depletion-curve without too much study, then cut out a template and test the curve and revise it where necessary.

The maximum value of ground-water discharge [see 1 of "References" at end of paper] is usually difficult to determine by the above procedure. The maximum may not have occurred during the period of record being studied unless a large winter flood is included. A rational extension upward of the observed curve until it becomes asymptotic to a vertical line will generally prove satisfactory. This is probably best accomplished on a natural-scale plot of the discharge. The maximum values of ground-water discharge used for various areas have varied from four to seven second-feet per square mile. Reasonable variation in these maximum values would have little effect on their use. In the case of the Schuylkill River, the maximum ground-water discharge was fixed at five second-feet per square mile. The normal ground-water depletion for Pottstown is tabulated in Table 1 and shown on Figure 4.

Ground-water storage-curve--The ground-water storage-curve is the integral of the depletion-curve, using the minimum ground-water discharge as a reference-point. This reference-discharge is the practical lower limit justified by the record in the determination of thenormal ground-water depletion-curve and its value should not be as low as the minimum of record. The amount of water discharged while the ground-water flow decreases from the maximum to the minimum discharge is simply the area under the depletion-curve. Unless the record includes an excessively long period without rainfall, it is not known how much ground-water the basin would ultimately discharge (unless the minimum flow is zero).

A convenient way to compute the storage-curve is to start with the minimum flow and tabulate values of the depletion-curve at short intervals of time. The increment of storage for an increment of time is then the product of the mean discharge and the corresponding increment of time. The storage-curve is obtained by plotting the sum of the increments of volume up to any particular discharge against that value of the discharge.

Table 1 gives the computations and curve B of Figure 3 is the ground-water storage-curve for the Schuylkill River Basin above Pottstown. The storage was computed above a reference-discharge of 200 second-feet and as plotted includes an adjustment to take care of the mechanical procedure adopted for separating ground-water discharge and surface-runoff or direct runoff. This is necessary owing to the fact that the recharge is not coincident with rainfall, but is distributed over a number of days following it. The rise of November 12, 1937 (Fig. 4) can be used as an example.

An arbitrary procedure is used in separating ground-water and surface-runoff. The recession AB is extended downward under the current-rise in the hydrograph just as the ground-water flow would have decreased had no rain occurred. At a convenient interval near the time of peak-flow of the rise, C, a straight line is drawn forward to meet the recession of the current-rise at the point F where surface-runoff ceases. Since the recharge is assumed to occur along line CF, instead of instantaneously along line DF, the triangular volume CDF must also be included in the computed recharge.

This correction can be included in the values of the storage-curve since the time-interval from C to D can be considered constant for a particular basin when applying the usual unit-hydrograph procedure. While not discussed in detail in this paper, a synthetic unit-hydrograph [2] for the Schuylkill River above Pottstown has a lag of 18 hours and a duration of 5.25 days when used with six-hour rainfall-data. The time-interval, C to D, can be taken as four days, and the correction for the storm of November 12 is (4/2) (F-D) in second-foot days. The storage-curve of Figure 3 has been adjusted so that the value of storage for a particular discharge includes a triangular volume computed for a recharge (extended over four days) from the reference-base of 200 second-feet up to the respective discharge. The adjusted storage-curve (B, Fig. 3 from Table 1, column 9) enables the analyst to determine the amount of water added to ground-water storage for a particular storm by obtaining the increment of storage corresponding to flows D and F.

Initial loss--Initial loss is defined as the maximum amount of precipitation that can occur under any given set of conditions without producing runoff. The relative amount is partly dependent on the position of the ground-water table and so it is correlated with ground-water discharge. Amount of evaporation and transpiration between rains also influences values of initial loss. Initial loss is a maximum when ground-water flow is at its minimum and vice versa. Accordingly, the initial loss is made zero at high ground-water discharge and a maximum at low ground-water discharge.

The maximum value of initial loss is determined from a study of storms occurring when ground-water discharge is at or near its minimum value. The values of rainfall that barely produce some runoff and the respective index-ground-water flows are noted for a number of storms.

For practical reasons initial loss is correlated with a ground-water discharge, index gwd, which has a value different than the actual discharge at the beginning of the storm. It is also well to tabulate a number of storms that give small amounts of runoff, since the initial loss for a given set of conditions can not be as great as the amount of precipitation which produced some runoff. If sufficient data are available, the tabulation can be made for various values of index gwd and the results correlated.

If an average value of initial loss is fixed for a particular ground-water discharge, all values of initial loss can be determined for other values of ground-water discharge according to the shape of the ground-water depletion-curve. This is an empirical short-cut and is accomplished by substituting initial loss for the time-scale of the ground-water depletion-curve.

A value of 1.50 inches was selected as the initial loss for an index gwd of 200 second-feet. The initial loss is assumed to be zero when point A (Fig. 1) of the ground-water table is at E. The ground-water discharge is considered to be a maximum (5750 second-feet) at this time and the index gwd for this basin is 2400 second-feet (six days after the maximum). All other values of initial loss are fixed according to the depletion-curve shape. Table 1 (column 10) gives this computation. An initial loss of 1.50 inches is tabulated opposite an index gwd of 200 second-feet and zero is placed opposite 2500 second-feet (value in tabulation nearest to a time of six days from the maximum). The intermediate values of initial loss are then directly proportional to the time-intervals between the corresponding values of index gwd. This assumes that initial loss increases directly proportional to time.

The values can be plotted as a curve showing an average value of initial loss for any value of index-ground-water discharge. In these studies initial loss is plotted against index gws instead of index gwd. The values of initial loss must be varied by the user to fit actual conditions of precipitation, temperature, humidity, etc., existing previous to the particular storm being analyzed. A basis for adjustment due to antecedent precipitation is to assume that initial loss after being wholly or partially satisfied by one storm will recover to its normal value with a straight-line variation in some period of time such as six days. The actual time necessary for such recovery depends on evaporation and transpiration and the variation is not directly proportional to time as evaporation and transpiration (other factors remaining constant) depend on moisture available.

Rainfall- and runoff-relations--The conception of runoff used in these analyses can now be restated: (1) The initial loss must be satisfied before any runoff can occur; (2) surface-runoff and recharge to the ground-water reservoir will then begin and the division between the two is fairly definite and depends on the condition of the soil or amount of soil-moisture; (3) in the relationships developed, index-ground-water discharge is used as a substitute for a soil-moisture index.

When enough rain has soaked into the soil to replenish the deficiency of capillary water, the index-ground-water discharge will not yet be at its maximum value. From this time on 100 per cent total runoff occurs with a decreasing percentage going into temporary storage in the surface-soil (gravity-water) which later drains into the ground-water reservoir and causes the index-ground-water discharge to approach its maximum value. When all the soil has been saturated, all rainfall becomes surface-runoff except for enough water to maintain ground-water discharge at its maximum.

This brings the discussion to the use of an index-ground-water discharge (called index gwd). It has been stated that for practical reasons the index is taken T days after the beginning of surface-runoff where T is the duration of the six-hour unit-hydrograph.

One of the reasons is that ground-water recharge is not reflected immediately at a gaging station but the accompanying increase in soil-moisture is immediate in its effect on surface-runoff potentiality. In the foregoing procedure the maximum discharge from ground-water recharge for a storm does not occur until the end of the surface-runoff. Consequently, it should be compared with the ground-water discharge that would have occurred at the same time, had there been no precipitation, to express the relative runoff-potentialities before and after a storm.

Using the storm of November 12, 1937 (Fig. 4), as an example, if F represents the runoff-potentiality of the soil after the rain, D is the comparable index gwd before the storm. It is to be noted that if the ground-water discharge, B, at the beginning of the storm were used as the index and the recharge from the storm were just enough to keep the ground-water flow equal to B at the end of surface-runoff, there would be no distinction as far as the index is concerned for storms occurring during the six-day interval.

The unit-hydrographs for most basins have durations of from five to seven days. This is approximately the time it takes for accretions to soil-water to become distributed throughout the soil. The use of the index at the end of surface-runoff coincides with this adjustment of soil-moisture. If the unit-hydrograph duration is not approximately six days, the index gwd can be taken as the value occurring six days after the beginning of runoff.

It will be recalled that initial loss was made equal to zero when ground-water discharge was at its maximum of 5750 second-feet and index gwd was 2500 second-feet. The index gwd can reach 2500 second-feet from two directions, either by depletion throughout the period of six days after a previous storm has raised the ground-water discharge to 5750 or as the result of a storm which has just increased the ground-water discharge to 2500 second-feet at the end of surface-runoff. If a storm occurs such that it recharges the ground-water discharge to the maximum of 5750 second-feet, rain falling shortly thereafter would occur as surface-runoff except for enough to hold the ground-water discharge at its maximum of 5750 second-feet which would be about 0.19 inch per day.

It is probable that the same effect occurs at any index gwd for very intense storms due to the inability of gravity-water to percolate rapidly enough. This places a limit on the amount of ground-water recharge that is possible from the usual-length storms.

There are a number of ways in which observed data can be analyzed in connection with the preceding discussion. Table 2 gives the observed data for some of the storms studied. In this example capillary water is correlated with index gwd and precipitation minus initial loss ($(P-L_1)$).

Table 2--Observed data for storms on Schuylkill River Basin above Pottstown, Pennsylvania

| Date | Approximate duration, hours | Precipitation,[a] inches | | Index gws, inches | Runoff, inches | | | Loss, $(P-L_1)$ minus total runoff, inches |
|---|---|---|---|---|---|---|---|---|
| | | Observed | Effective, $(P-L_1)$[b] | | Total | Surface | Ground-water | |
| Oct. 2, 1929 | 24 | 3.75 | 3.45 | 0.31 | 1.87 | 0.93 | 0.94 | 1.58 |
| Sep. 2, 1931 | 6 | 1.25 | 0.31 | 0.20 | 0.25 | 0.12 | 0.13 | 0.06 |
| Oct. 5, 1932 | 30 | 4.00 | 2.50 | 0.00 | 0.92 | 0.35 | 0.57 | 1.58 |
| Aug. 22, 1933 | 24 | 2.61 | 2.20 | 0.61 | 1.38 | 0.75 | 0.63 | 0.82 |
| Aug. 24, 1933 | 24 | 4.27 | 4.25 | 1.22 | 3.79 | 2.92 | 0.87 | 0.46 |
| July 7, 1934 | 12 | 1.39 | 0.71 | 0.37 | 0.21 | 0.11 | 0.10 | 0.50 |
| Sep. 7, 1934 | 24 | 1.85 | 1.37 | 0.25 | 0.65 | 0.23 | 0.42 | 0.72 |
| Sep. 30, 1934 | 12 | 2.72 | 2.43 | 0.77 | 1.74 | 0.88 | 0.86 | 0.69 |
| July 8, 1935 | 24 | 5.88 | 5.17 | 0.34 | 3.36 | 1.88 | 1.48 | 1.81 |
| Apr. 6, 1936 | 12 | 1.85 | 1.72 | 1.09 | 1.67 | 0.85 | 0.82 | 0.05 |

[a] Average of a selected group of precipitation-stations.

[b] Includes adjustments to initial loss for storms occurring in preceding six days.

Curve D of Figure 3 shows a relation between index gws and accumulated capillary water. This assumes that, as capillary water is increased, a related amount of water is added to ground-water storage. Curve C shows a relation between $(P-L_1)$ and accumulated capillary water. Both curves are conveniently developed on the same diagram with cumulative capillary water, common to both curves, as the abscissa. Index gws is the ordinate for D and accumulative $(P-L_1)$ is the ordinate for C. The initial or beginning point for the accumulations is common to both curves and can be made the origin in this case since the index gws of zero value corresponds to a discharge of 200 second-feet which is the practical lower limit for the studies.

A trial curve D for an average relation between index gws and cumulative capillary water is drawn from a study of the data in Table 2. The storms occurring with low values of index gws are used to fix an approximate slope for the lower section. The storm of October 5, 1932, occurred after a long dry spell and gave a loss or addition to capillary water of 1.58 inches and an addition to ground-water storage of 0.57 inch. The trial D curve can be drawn through this point or an adjusted point of less recharge since the storm followed a dry period. The data for the other storms are then plotted using trial D curve to determine the initial values (enter diagram with index gws and obtain an initial value of cumulative capillary water) and the final values are plotted on the diagram (index gws plus ground-water recharge against initial cumulative capillary water plus the loss for the storm). A revised curve D is then drawn to obtain a better average relation.

A second use of curve D is now possible. Curve D and the index gws fix an initial value of accumulated capillary water with which to enter curve C and obtain an initial value of accumulated $(P-L_1)$. A trial curve C is obtained by plotting the data for several storms occurring when index gws was at or near its minimum. For the storm of October 5, 1932, the trial curve can be drawn from the origin through a value of cumulative capillary water of 1.58 inches and a cumulative value of $(P-L_1)$ of 2.50 inches. With a trial curve established for the lower range, the data for the storms having higher index gws can be plotted, etc., and the trial curve C extended and revised. The shape of both C and D depends on the relative amount of area with the various depths to the ground-water table (represented by width of the strip of land of Fig. 1)

In summary, curve D and the index gws fix an initial value of cumulative capillary water. The initial value of cumulative capillary water and curve C give an initial value of accumulated $(P-L_1)$. The value of $(P-L_1)$ for the current storm is added to the initial value of $(P-L_1)$ to obtain the final value of $(P-L_1)$. The final value of $(P-L_1)$ and curve C fix the final value of cumulative capillary water. The increment of capillary water is the loss for the storm and is subtracted from the value of $(P-L_1)$ for the storm to obtain the total runoff for the storm. The final value of accumulated $(P-L_1)$ taken back to curve D gives the final ground-water storage. The increment of ground-water storage for the storm is the recharge for the storm.

If curve D were to be used in the final procedure for determination of ground-water recharge, upper- and lower-limit curves would be added to the diagram to take care of seasonal changes in amount of recharge. However, curve A (Fig. 3) will be developed and used to determine ground-water recharge directly from total runoff.

Curve A is obtained by plotting the data for observed isolated storms. It has been noted on various areas that there appears to be a maximum value of ground-water recharge occurring from isolated storms. The assumption has already been made that it takes about six days for additions to soil-moisture to become distributed vertically. Referring to Figure 1, it would appear that for basins which have considerable area with great depth to the ground-water table as at D B, the maximum amount of recharge can be reached before all the capillary deficiency has been replaced. That is, a zone of saturated soil is developed parallel to E D, which largely limits the amount of water penetrating the surface. Thus the data for the storms of August 22 and 24 (separated by only 12 hours) should be plotted as a single storm.

When two storms occur within six days of each other, curve A is used as a mass-curve assuming a straight-line decrease in the effect of the recharge from the first storm on the second storm. For example, if the second storm occurs two days after the first and the first storm has a recharge of 0.99 inch from a total runoff of 2.00 inches (middle branch of curve A) the initial recharge for the second storm would be 0.66 inch (4/6 of 0.99) which fixes an initial total runoff of 1.22 inches (middle branch). The total runoff for the second storm is then added to the initial total runoff of 1.22 inches to obtain a final total runoff. The final total runoff and curve A give the final recharge which determines the increment of recharge for the second storm. However, it must be remembered that, regardless of the value of recharge obtained from curve A, the recharge for any storm can not be greater than the amount required to raise ground-water storage to its maximum of 2.34 inches.

The three branches of curve A are used for various periods as labeled. The lower branch is used only in the summer when the capillary water reaches a relatively low amount (high capillary deficiency) and temperatures are high. Ground-water recharge is affected by temperatures immediately after a storm as well as by conditions before the storm. The considerable evaporation which occurs after a storm (most of it within six days) comes partly from the gravity-water which might have reached the ground-water table if it had not evaporated. The upper branch is used only in the winter periods when the amount of capillary water is large and temperatures are low.

Adjustments to procedure for computation of daily runoff--The rainfall-runoff relations developed so far are all that would be required for flood-forecasting. It is assumed that rational adjustments would be made by the forecaster. These would consist of adjustments to values of the initial loss obtained from curve E (70°) and a corresponding adjustment of the index gws which fixes the initial values on curves D and C and is assumed to represent the existing soil-conditions just before the storm.

The use of an index gws is a great help where forecasts are made only for the larger storms and where personnel is limited in proportion to the number of basins for which forecasts are desired. Thus, when a critical period develops, the forecaster through a determination of the index gwd (which fixes index gws) has available an approximate index of soil-conditions without making an extensive study of previous storms.

However, the procedure has certain weaknesses. The storms used in deriving the curves of Figure 3 are almost all summer storms, partly by intent and partly because summer storms are usually more isolated and do not require consideration of snow. The use of curve D and a value of index gws assumes a constant temperature or evaporation- and transpiration-opportunity since the change in capillary water when ground-water storage decreases from one value to another is the same regardless of possible differences in these quantities for different periods of the year. This follows through the use of a single normal ground-water depletion-curve.

Temperature (degree-days above 30° F) is now assumed as an index of evaporation and transpiration, more because of its availability than its suitableness. The average temperature for the Schuylkill River Basin above Pottstown for the summer is about 70° F. The average relations represented by curve D (Fig. 3) are thus for an average temperature of approximately 70°. If the capillary water decreased from a value of 2.55 inches to zero while the ground-water discharge depleted from 5750 to 200 second-feet (64 days), the loss would amount to 0.001 inch per degree-day above 30° F. Using this amount as a basis, a procedure has been adopted for the determination of existing capillary water by this means rather than by curve D, although the latter is used to obtain a starting point in October. Since a study of storms occurring in the spring after transpiration becomes appreciable indicates that the capillary water depletes faster than ground-water storage, the value of loss per degree-day is varied to take care of the greater evaporation- and transpiration-opportunity from April to September. A factor of 0.0015 is used during the growing season and 0.001 during the remainder of the year.

Initial loss has been assumed to depend on the position of the ground-water table and temperature. In the section on initial loss only one curve was mentioned. This was the 70° branch of E (Fig. 3). The small amount of 0.20-inch initial loss is assumed as the maximum possible for an average temperature of 30° F since the preceding storm. At least six days must have elapsed, otherwise the value shown by the curves is decreased by an amount inversely proportional to time since the preceding storm. The initial-loss curve for 50° F is based on a maximum loss of 0.85 inch (average of 0.20 and 1.50). As a matter of interest, the five-year average annual difference between rainfall and runoff is 20.10 inches and the average temperature is 53°.6 F corresponding to a total loss of 0.0023 inch per degree-day above 30° F. If periods of rainfall were eliminated this rate would be considerably higher. This indicates that initial loss accounts for about half of the total loss since the total loss exclusive of initial loss is somewhere between 0.001 and 0.0015 inch per degree-day above 30° F.

Example--The runoff of the Schuylkill River above Pottstown, Pennsylvania, has been computed for the water-year 1937-38 to illustrate the use of the curves of Figure 3. The Schuylkill Basin is mountainous in its upper reaches while the lower section consists of broad, rich, rolling agricultural lands. The headwaters are in the coal-measures and the lower section of the River cuts through formations of shale, sandstone, and limestone. The precipitation varies considerably between the upper and lower sections depending on the type of storm and is usually heavier on the headwaters. Values of precipitation were based on the standard geometric weighting which assumes any point to have the same amount of rainfall as that of the nearest station. Six United States Weather Bureau stations were used for most of the year and seven for the remainder of the period. The distribution was poor since two stations--Hamburg and Reading--controlled over half the Basin. The temperatures used are those at Hamburg. This station was moved to Port Clinton during the period.

The problems of melting snow have not been discussed and fortunately the snowfall was light during the water-year 1937-38. Temperatures and the notes of one observer were used to determine whether or not the observed precipitation was in the form of snow and whether it melted on falling or later.

An arbitrary adjustment of the normal ground-water depletion-curve is made during the period from the middle of September to the middle of April whenever the ground-water discharge is less than 500 second-feet. The template of the depletion-curve is shifted vertically an amount equal to 150 second-feet. Ground-water discharge during the period mentioned often remains fairly constant in spite of no recharge. This is mainly due to decreased evaporation and transpiration after the growing season is over.

Since this paper is not concerned with the shaping of runoff into a continuous graph of

Table 3--Computation of runoff for Schuylkill River above Pottstown, Pennsylvania, 1937-38

| Date | Index gwd, second-feet | Precip. and (P-L$_1$), inches | Initial loss, L$_1$, inches | Average temperature and degree-days since previous runoff | Loss since previous runoff, inches | Cumulative values | | Total runoff, inches | Index gwd and recharge, inches | Surface-runoff, inches |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Capillary water, inches | (P-L$_1$), inches | | | |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) |
| Oct. 3 | ... | 0.02 | .... | .. | .... | .... | .... | .... | .... | .... |
| 5 | ... | 0.15 | .... | .. | .... | .... | .... | .... | .... | .... |
| 9 | ... | 0.16 | .... | .. | .... | .... | .... | .... | .... | .... |
| 13 | ... | 0.01 | .... | .. | .... | .... | .... | .... | .... | .... |
| 19 | 350 | 3.05 | 0.93 | .. | .... | 0.53 | 0.75 | .... | 0.20 | .... |
| | ... | 2.00 | 1.05 | .. | .... | 1.17 | 2.00 | 0.83 | 0.46 | 0.37 |
| | 880 | .... | .... | .. | .... | 1.70 | 2.75 | .... | 0.66 | .... |
| 23 | 750 | 2.61 | 0.29 | 53 | 0.07 | 1.63 | 2.60 | .... | 0.57 | .... |
| | ... | 2.47 | 0.14 | 69 | .... | 0.77 | 2.47 | 1.70 | 0.80 | 0.90 |
| | 2250 | .... | .... | .. | .... | 2.40 | 5.07 | .... | 1.37 | .... |
| 27 | 1620 | 0.90 | 0.06 | 46 | 0.06 | 2.34 | 4.72 | .... | 1.08 | .... |
| | .... | 0.87 | 0.03 | 64 | .... | 0.12 | 0.87 | 0.75 | 0.35 | 0.40 |
| | 2400 | .... | .... | .. | .... | 2.46 | 5.59 | .... | 1.43 | .... |
| Jan. 1 | 850 | 0.63 | 0.09 | 34 | 0.01 | 2.47 | 5.65 | .... | 0.65 | .... |
| | .... | 0.59 | 0.04 | 12 | .... | 0.04 | 0.59 | 0.55 | 0.41 | 0.14 |
| | 1600 | .... | .... | .. | .... | 2.51 | 6.24 | .... | 1.06 | .... |
| 7 | 1050 | 0.35 | 0.05 | 33 | 0.02 | 2.49 | 5.85 | .... | 0.77 | .... |
| | .... | 0.30 | .... | 15 | .... | 0.02 | 0.30 | 0.28 | 0.22 | 0.06 |
| | 1450 | .... | .... | .. | .... | 2.51 | 6.15 | .... | 0.99 | .... |
| 12 | .... | 0.37$^s$ | .... | .. | .... | .... | .... | .... | .... | .... |
| 17 | .... | 0.04$^s$ | .... | .. | .... | .... | .... | .... | .... | .... |
| 21 | .... | 0.31$^s$ | .... | .. | .... | .... | .... | .... | .... | .... |
| 24 | 580 | $\underline{1.32}$ | 0.04 | 26 | 0.02 | 2.49 | 5.85 | .... | 0.44 | .... |
| | .... | 2.04 | 0.16$^a$ | 19 | .... | 0.06 | 1.88 | 1.82 | 0.99 | 0.83 |
| | 2400 | 1.88 | .... | .. | .... | 2.55 | 7.73 | .... | 1.43 | .... |
| 31 | 1350 | 0.17 | 0.01 | 26 | 0.01 | 2.54 | 6.85 | .... | 0.94 | .... |
| | .... | 0.16 | .... | 8 | .... | 0.01 | 0.16 | 0.15 | 0.11 | 0.04 |
| | 1570 | .... | .... | .. | .... | 2.55 | 7.01 | .... | 1.05 | .... |
| July 1 | 1240 | 0.35 | 0.21 | 64 | 0.18 | 1.93 | 3.27 | .... | 0.87 | .... |
| | .... | 0.21 | 0.14 | 119 | .... | 0.07 | 0.21 | 0.14 | 0.09 | 0.05 |
| | 1400 | .... | .... | ... | .... | 2.00 | 3.48 | .... | 0.96 | .... |
| 9 | 860 | 0.43 | 0.39 | 73 | 0.48 | 1.52 | 2.38 | .... | 0.65 | .... |
| | .... | 0.04 | .... | 322 | .... | 0.02 | 0.04 | 0.02 | 0.01 | 0.01 |
| | 880 | .... | .... | ... | .... | 1.54 | 2.42 | .... | 0.66 | .... |
| 11 | 790 | 1.98 | 0.51 | 80 | 0.15 | 1.39 | 2.14 | .... | 0.60 | .... |
| | .... | 1.73 | 0.25 | 100 | .... | 0.75 | 1.73 | 0.98 | 0.55 | 0.43 |
| | 1780 | .... | .... | ... | .... | 2.14 | 3.87 | .... | 1.15 | .... |
| 15 | 1330 | 0.31 | 0.29 | 78 | 0.22 | 1.92 | 3.23 | .... | 0.92 | .... |
| | .... | 0.11 | 0.20 | 144 | .... | 0.04 | 0.11 | 0.07 | 0.04 | 0.03 |
| | 1400 | .... | .... | ... | .... | 1.96 | 3.34 | .... | 0.96 | .... |
| 18- | 1050 | 1.48 | 0.34 | 78 | 0.29 | 1.67 | 2.68 | .... | 0.76 | .... |
| 20 | .... | 1.26 | 0.22 | 192 | .... | 0.49 | 1.26 | 0.77 | 0.43 | 0.34 |
| | 1850 | .... | .... | ... | .... | 2.16 | 3.94 | .... | 1.19 | .... |
| 21- | 1470 | 2.32 | 0.20 | 72 | 0.09 | 2.07 | 3.64 | .... | 1.00 | .... |
| 23 | .... | 2.22 | 0.10 | 63 | .... | 0.42 | 2.22 | 1.80 | 0.83 | 0.97 |
| | 3600 | .... | .... | ... | .... | 2.49 | 5.86 | .... | 1.83 | .... |
| 29 | 1920 | 0.42 | 0.12 | 81 | 0.42 | 2.07 | 3.64 | .... | 1.22 | .... |
| | .... | 0.30 | .... | 280 | .... | 0.09 | 0.30 | 0.21 | 0.12 | 0.09 |
| | 2180 | .... | .... | ... | .... | 2.16 | 3.94 | .... | 1.34 | .... |

[s] Indicates precipitation was in form of snow and did not melt.

[a] Includes 0.12-inch evaporation from snow.

discharge, the example is carried out by means of a tabulation in conjunction with a graphical record of computed ground-water discharge. No extreme care has been taken to fix beginning and ending of surface-runoff for the various storms. The dates for the storms were taken as the day on which most of the precipitation occurred. Storms occurring close together were generally taken as one storm to save time and space. Table 3 gives the computation for October, January, and July. Figure 4 shows the graphical record of the ground-water discharge computations and the observed mean daily discharge except for the higher flows. One exception to a fixed procedure will be noted on Figure 4. There is a discontinuity in the line of computed ground-water discharge on May 9. The observed recession of runoff after April 24 is unusual and difficult to account for since there was no rain after April 22 except 0.09 inch on April 29. The slow depletion may have been due to increased mine-drainage. At any rate, it was assumed that the observed value of discharge for May 9 was known and a new depletion was started from that point. Table 4 gives a monthly comparison of observed and computed runoff.

Table 4--Observed and computed runoff for Schuylkill River above Pottstown, Pennsylvania, 1937-38

| Month | Precipitation, inches | Runoff, inches | |
|---|---|---|---|
| | | Observed | Computed |
| October | 6.90 | 2.29 | 2.40 |
| November | 2.52 | 1.89 | 1.98 |
| December | 1.66 | 1.54 | 1.62 |
| January | 3.19 | 2.36 | 2.30 |
| February | 2.21 | 2.06 | 1.96 |
| March | 2.60 | 2.34 | 2.31 |
| April | 2.51 | 1.75 | 1.54 |
| May | 3.13 | 1.20 | 1.10 |
| June | 5.87 | 1.51 | 1.38 |
| July | 7.29 | 2.97 | 3.62 |
| August | 2.94 | 1.49 | 1.87 |
| September | 5.90 | 1.42 | 1.21 |
| Year | 46.72 | 22.82 | 23.29 |

The tabulations of Table 3 are merely for convenience and could be carried out in other ways. Each storm requires three lines if the precipitation is greater than the initial loss. When it is evident that the initial loss is greater than the precipitation, the precipitation is all that is noted in the Table. Where adjustments are required to the initial loss, the value obtained from the curves is tabulated on the first line and the adjusted value on the second. Using the storm of October 23, as an example the index gwd (computed) from Figure 4 is 750 second-feet (ground-water discharge on October 29). The corresponding storage from B (Fig. 3), is 0.57 inch which is tabulated in column (10), first line. The average temperature since the previous runoff is 53° F and is tabulated in column (5), first line, and the number of degree-days above 30° F, 69 (three days at 53° F), is placed immediately below on line 2. The temperature of 53° F, index gws of 0.57 inch and E (Fig. 3), furnish an initial loss of 0.29 inch (column 4, line 1) which is reduced to 0.14 inch due to the storm having occurred three days before (3/6 of 0.29) and placed on line 2. The precipitation of 2.61 inches has been placed in column (3), line 1, and this value less the initial loss of 0.14 leaves a $(P-L_1)$ of 2.47 which is placed on line 2.

The loss from capillary water since the previous runoff, column (6), is 0.07 inch (69 degree-days times 0.001) which subtracted from the previous value of cumulative capillary water of 1.70 inches gives an initial value of cumulative capillary water of 1.63 inches (column 7, line 1). This value and curve C (Fig. 3) give the initial value of $(P-L_1)$ of 2.60 inches (column 8, line 1). The current $(P-L_1)$ of 2.47 inches is added giving a final value of $(P-L_1)$ of 5.07 inches (line 3). Curve C shows a final value of cumulative capillary water of 2.40 (column 7, line 3) inches for a value of $(P-L_1)$ of 5.07, which means a loss for the storm of 0.77 inch (line 2). This loss subtracted from 2.47 gives a total runoff of 1.70 inches (column 9, line 2).

Curve A (average) is used to obtain the ground-water recharge remembering that 3/6 of the effect of recharge from the storm of October 19, still exists. Thus, 3/6 of 0.46 (previous recharge) is 0.23 which gives (curve A) an initial total runoff of 0.40 and 0.40 plus 1.70 equals a final total runoff of 2.10 which gives a final value of recharge of 1.03 representing an increment of recharge of 0.80 inch. This step has not been shown in the Table except to record the recharge of 0.80 inch in column (10), line 2. The surface-runoff for the storm is then obtained by subtracting the recharge of 0.80 inch from the total runoff of 1.70 which is recorded as 0.90 inch in column (11).

The final storage of 1.37 inches (column 10, line 3) is obtained by adding the recharge of 0.80 inch to the index gws of 0.57 inch. In a strict analysis this could be done only for storms of 18 hours' duration since the index gws is taken six days from the beginning of $(P-L_1)$ and the unit-hydrograph for the basin has a duration of 5.25 days. The error introduced in this example by neglecting the duration of the storms is negligible. The value of storage of 1.37 inches and curve B give a final ground-water discharge of 2250 second-feet which is placed on line 3, column (2), and used on Figure 4 to fix the position of the next ground-water depletion.

Conclusions--The results of the computations for the water-year 1937-38 (Table 4) are fair and may be better than could be normally expected. The differences in July and August between observed and computed runoff are of the same magnitude as the difference for the year. The errors for July and August are the result of computations for the rainfall occurring in the latter part of July and it is difficult to understand the small amount of observed runoff. The rains were concentrated on the lower basin and consisted of intermittent rainfall of high intensity. Evaporation and transpiration between the showers may have been greater than that accounted for by the procedure.

In this connection, the initial loss as obtained from E (Fig. 3) is limited when the ground-water table is near the surface. This is still assumed to be correct as regards initial loss, but disregards the fact that the total loss by evaporation (immediately after a rain) may be as great when the water-table is high as it is when the water-table is low. Thus when the temperature and index gws are high, a greater loss is occurring from the capillary water than accounted for by the constant factor of 0.0015 inch per degree-day above 30° F. A similar difficulty is encountered when the temperature is high and the index gws is low. In this case the value of initial loss from curve E is probably greater than can develop in six days as assumed. The procedure as used gives no runoff for a temperature of 70° F, an index gws of zero, and precipitation of 1.50 inches every seven days.

Both of the above difficulties are the result of using initial loss for more than is consistent with its definition. Since the initial loss is developed first after a storm occurs, it has been used to take care of the fact that evaporation is greatest immediately after a storm when the moisture-supply is greatest. The procedure might be improved by computing the total evaporation and transpiration between storms on a basis of temperature (at a gradually decreasing rate) and then subtracting the initial loss from the total loss. The remainder of the loss would then be subtracted from the accumulated value of capillary water.

Another difficulty encountered in the computations was the greater than usual number of spotty storms. There were numerous cases of amounts of precipitation of over two inches at one or two stations and practically no rainfall at the other stations. If the average basin-rainfall were less than the initial loss, the procedure gave no runoff. While not attempted in this study, the difficulty can be overcome by eliminating the area on which the rainfall is less than the initial loss and then making the computations for the remainder of the area. The values of runoff obtained by use of the curves must be reduced in proportion to the area having no runoff.

Finally, the studies indicate that the accuracy of the general procedure is limited only by the ability to determine evaporation and transpiration between storms and to measure and deal with variations of rainfall over the basin.

## Appendix--Glossary and symbols

Capillary capacity--Amount of water that a soil can retain against the action of gravity.

Capillary deficiency--Amount of water necessary to raise capillary water-content up to capillary capacity.

Capillary water--Water retained in the soil mainly by molecular attraction against the action of gravity and the greater part of which can be abstracted by evaporation and transpiration.

Gravity-water--Water that moves through the soil under the influence of gravity.

Ground-water recharge--The water which reaches the zone of saturation from a particular storm.

Ground-water runoff--That part of the runoff which reaches the surface drainage-channels from the zone of saturation.

Index ground-water discharge (index gwd)--The discharge of ground-water runoff at a gaging station "T" days after the beginning of surface-runoff (on the same depletion assuming no rise) where T is the duration of the unit-hydrograph for the basin.

Index ground-water storage (index gws)--The ground-water storage corresponding to index gwd.

Initial loss, $L_i$--The maximum amount of precipitation that can occur under any given set of conditions without producing runoff.

Surface-runoff--Usually defined as the runoff reaching the surface drainage-channels without penetrating the ground-surface. As actually used, surface-runoff usually includes considerable subsurface storm-flow and might better be termed direct runoff, since it consists of the discharge in excess of a base or ground-water flow which passes a gaging station within a rational period of time subsequent to the storm causing the rise.

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